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Technical Report No. 24

AIRMASSES, STREAMLINES, AND THE BOREAL FOREST

Reid A. Bryson

(with appendix: Non-linear
Parameter Estimation for the
Partial Collective Model of
Airmass Analysis by
Donald R. Johnson)

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University of Wisconsin
Department of Meteorology
Madison, Wisconsin 53706
February, 1966

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Model of Airmass Analysis
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Task No. NR 387-022 ONR Contract No.: 1202(07)
and NSF GP - 444

The research reported in this document has
been sponsored by the Geography Branch of
the United States Office of Naval Research
and by the National Science Foundation.

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ABSTRACT

The ~~analysis~~ of July airmass frequency distribution over Canada is analyzed by daily computation of trajectories from grid intersections back to source regions. A zone of rapid transition from Arctic Air dominance to Pacific Air dominance is found to lie along the northern border of the boreal forest, suggesting that the summer airmass distribution might be an important causal factor for the distribution of forest versus tundra.

An independent analysis of July airmass frequency distribution by resolution of the daily maximum temperature frequency distribution into partial collectives (component normal distributions) yields results very similar to the trajectory analysis but with more detail. This analysis suggests that airmass dominance might be of importance to other biotic regions as well as the boreal forest and tundra.

A final analysis using monthly resultant wind streamlines near the surface indicates that mean airstreams and confluences between airstreams define climatic regions with a distinctive annual march of airstream (and in the mean, airmass) dominance. These regions show a clear congruence with several major biotic regions. These analyses strongly suggest that the boreal forest occupies the region between the mean (or modal) southern boundary of Arctic Air in winter and the mean southern boundary of Arctic Air in summer.



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PREFACE

According to Hare (1951), ecological climatology is based on the concept that "vegetation and soils are mirrors of the normal climate" and that "soil and vegetation maps divided into regions ought therefore to give us a useful method of defining rational climatic regions". As he pointed out, this is the basis for the familiar climatic classifications of Köppen and Thornthwaite. In the same article, he discussed the attempts to find climatic values of the temperature which would correspond to the tundra-Boreal forest border, but concluded that the attempts were "hit-and-miss affairs with no rational basis".

Certain aspects of this approach leave the student of climates unsatisfied, and with unanswered questions. Even if "climate is the ultimate ecological control" (Hare, op. cit. p.953), is it only the temperature climate that is causative to the variety of distinctive biota of the north? This implies that certain temperature combinations alone result in certain plant communities, holding site and substrate constant. How does one relate a dichotomized biotic distribution to a temperature continuum? Or is there really a natural regionalization of climatic complexes which results ultimately in biotic regions? It is towards the answer of this last question that the present study is directed.

For many years the meteorologist has recognized the existence of naturally occurring atmospheric complexes, subsumed under the concept of the airmass. Arctic airmasses, for example, have a certain temperature range in each place and season, and characteristic moisture, turbidity, and structure as well. It is the distinctive combination of these elements into a recognizable complex that is at the heart of airmass analysis. He has also recognized the

natural, more or less sharp, boundaries between these complexes as the well-known "front" or "frontal zone". If it can be shown that these fronts have distinguishable mean locations, which change with the seasons so as to create more-or-less homogeneous regions which differ from each other in airmass regimen, then we will have obtained a discontinuous pattern of climatic complexes independent of the biological data which can be compared with the biotic distributions. If, then, there is seen to be a correspondence of patterns and one assumes that climate is the ultimate ecological control, perhaps our insight into the climatic-biotic relationship will have been deepened.

This study has been under way for at least ten years, yet cannot be considered complete. Too many questions and uncertainties remain; but the results summarized here are sufficiently encouraging to justify entering into the enormous task of data processing and analysis that will be required to expand the techniques and explore other regions and possibilities. In the already considerable effort the author has been aided by students and colleagues too numerous to list, but two in particular must be mentioned because of their special contributions: Prof. Lyle H. Horn, who did one of the first trajectory analyses described herein, and Prof. Ernest Sabbagh, who actually wrote a first draft of chapter 2. Their help, and that of the many others, is most gratefully acknowledged.

AIRMASSES, STREAMLINES, AND THE BOREAL FOREST

1. INTRODUCTION

In the course of field investigation of the climate and climatically related terrain parameters in north central Canada, it has been observed that in mid-summer the northern forest border is frequently the site of more disturbed weather than the region either to the north or to the south. In-flight observations of wind changes across this disturbed area strongly suggest the frequent presence of a front near the forest border. Many days of ground observation from just north of the forest border at Ennadai Aeradio Station ($61^{\circ} 08' \text{ N}$, $100^{\circ} 51' \text{ W}$) also included notice of maximum cloud development over the boreal forest to the south.

That fronts and wave cyclones are more common in the general vicinity of tree line than over either the tundra or boreal forest proper is rather easy to demonstrate through the examination of synoptic charts, though the wide spacing of weather stations makes precise location difficult (Reed 1959). In turn this implies that the dominance of a particular air mass over the tundra and a different air mass over the boreal forest may be of more than casual interest to the scholar concerned with the possible causal relationship between climate and biotic communities in the north. It is the purpose of this paper to explore the sources and distribution of air masses in order to add to the synoptic evidence that the tree line is indeed related to the mean (or perhaps modal) frontal zone. In addition, we shall consider whether the southern edge of the boreal forest is also a meteorologically defined boundary, and suggest some other climatic-biotic relationships. In this study the paucity of weather stations, and the near non-existence of aerological observations in the

northern area, require the use of rather non-standard analytical techniques. Fortunately the area of concern is relatively simple geographically--low surface of slight relief, homogeneous, continental interior, with only a few major biotic regions.

One approach to the study of air mass frequencies is that of Brunnschweiler (1952) who applied to the North American continent the technique he had used earlier in the analysis of European air mass distributions. Though the technique of utilizing the air mass identification placed on the synoptic chart by the analyst may be applicable in Europe, it is of doubtful validity in the identification of any but maritime tropical air in North America. The manuscript maps from which Brunnschweiler's frequencies were determined reflected little thoughtful or objective discrimination between the colder varieties of air. The typical American analyst of a decade or two ago was likely to class all cold air coming from Canada as cP with little consideration of true source, and apply even less discrimination to the air masses of northern Canada. We shall, therefore, reject the frequencies found by Brunnschweiler ab initio as showing much too great a predominance of cP air in southern Canada and the northern United States.

Penner (1955) recognized four main air masses over North America (mT, mP, mA, and cA). Canadian analysis generally identifies three fronts in winter: the polar front which separates mT and mP air, the maritime arctic front which separates mP and mA air, and the continental arctic front which separates mA from cA air. In summer, only two fronts are distinguished since there is no source for continental arctic air. Reed (1959 op. cit.) verifies the existence of this frontal scheme but emphasizes the impermanency of the fronts.

2. AIRMASS FREQUENCY ANALYSIS BY THE TRAJECTORY METHOD

Since every air mass (in the classical sense) must have a source, tracing the air trajectory back to this source serves to eliminate some of the uncertainty of terminology which arises when one must decide how a particular column of air acquired its characteristics. For our present purpose, the trajectories were followed back only to the borders of Canada. On this basis four external sources were defined: Arctic, Pacific, Atlantic, and United States. Only for the U. S. border did this lead to uncertainty, for air of both Pacific and Gulf origin crosses the Canadian border east of the Rocky Mountains, but for our purposes the admixture will be neglected. A fifth, but rather unimportant, source was found from those trajectories which showed a long residence time in an anti-cyclone located over Hudson Bay. For July this truly Canadian source was uncommon.

On the basis of the trajectories, frequency of occurrence of the various air masses was plotted for each five degree latitude and longitude grid segment for the ten months of July from the years 1945-51 and 1954-56. The geostrophic trajectories from twelve-hourly surface synoptic charts were used.

As expected, air originating over the Arctic Ocean occurs with the highest frequency over the Arctic Archipelago. (Figure 1) The southward decrease in the frequency of occurrence of Arctic air is fairly rapid. At 70°N latitude Arctic air prevails with a frequency of 90 percent or more, while at 60°N latitude the frequency of occurrence varies from less than 10 percent at 140°W longitude on the west coast to 50 percent in the vicinity of Hudson Bay, decreasing again east of the Bay to 30 percent along the east coast in the vicinity of northern Labrador, at 60°W longitude. The isolines dip southeast over the Hudson Bay area, portraying a tongue of high frequency of Arctic air spreading southward over the Bay. Hudson Bay appears as a cold region in

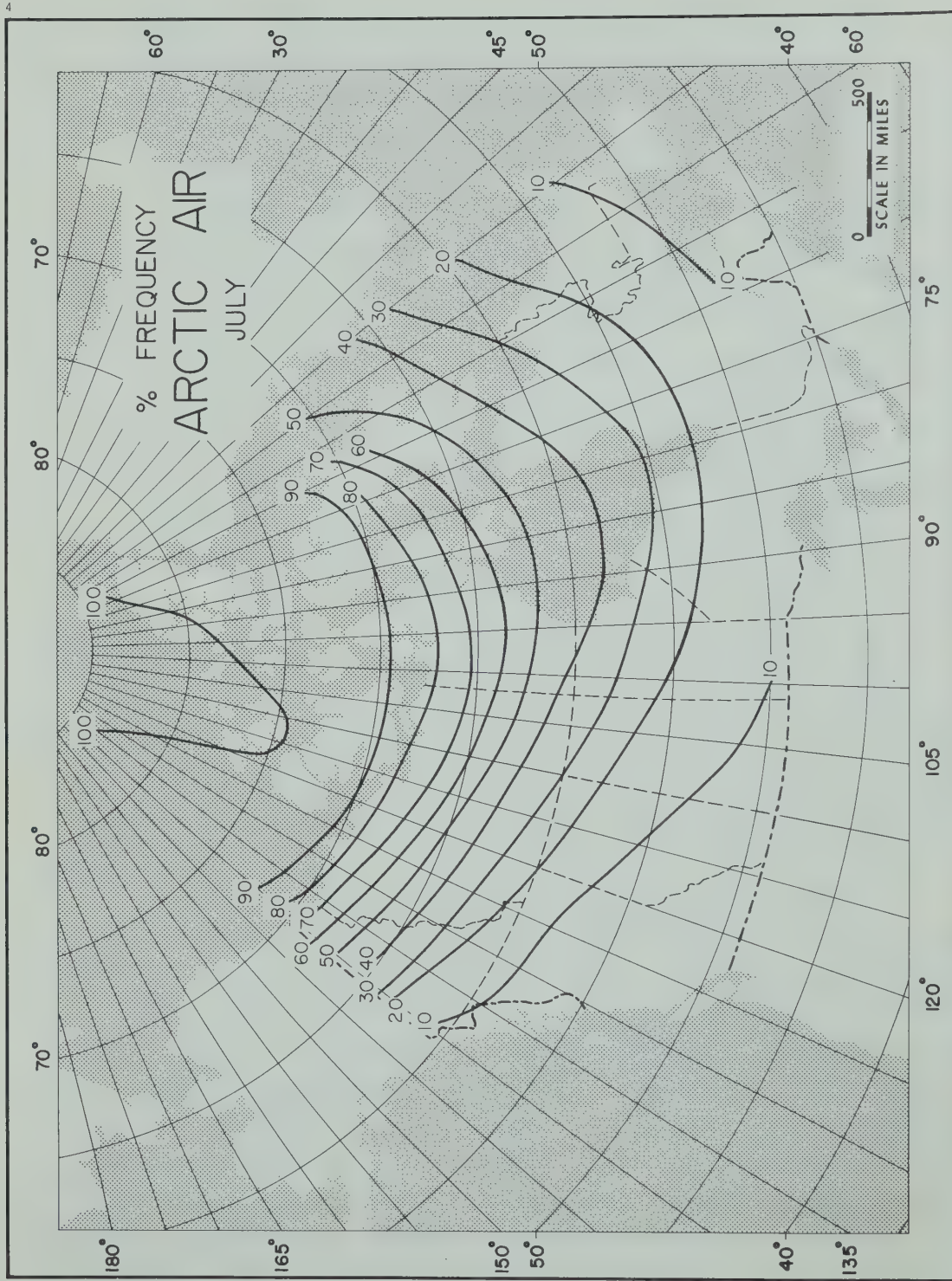


Figure 1. Isopleths of the percentage frequency of occurrence of Arctic air over Canada in July, determined by computing trajectories back to the source from each grid intersection for each July day in the period 1945-51, 1954-56.

the pattern of July daily temperature mean isotherms, the pattern being particularly pronounced in the case of the July daily maximum temperature (Thomas 1953).

Throughout British Columbia Arctic air is rare, penetrating west of the cordillera on less than 5 percent of the days in July. Over the central part of the continent the frequency of modified Arctic air reaching the United States is only about 10 percent.

The distribution pattern of Pacific air shows a close relationship to the mean atmospheric circulation. (Figure 2) The core area of over 90 percent frequency of Pacific air occurs in proximity to the source region west of the cordillera. The eastward spread of Pacific air is strongest in the region of the main stream of westerly wind in July at about 50° to 55° N latitude. From west to east the occurrence of Pacific air decreases generally, the gradient being strongest in the Prairie Provinces and weakest east of Hudson Bay. The westerly flow carries Pacific air deep into the continent so that, despite the mountain barriers obstructing the eastward flow of air, Churchill, Manitoba, located more than 1000 miles from the source region, experiences air from the Pacific one-third of the time, a frequency almost equal to that of Arctic air and many times the frequency of Atlantic air.

From the core region for Pacific air a much stronger gradient occurs in a northeasterly direction towards the region dominated by Arctic air. The pattern of occurrence of Pacific air, therefore, is one that reveals a change from almost 100 percent frequency on the coast of British Columbia to 10 percent frequency on the Newfoundland coast, to less than 5 percent in the Canadian Archipelago. On the other hand, the atmospheric circulation does not favor the deep continental penetration of Atlantic air. Air of Atlantic origin occurs with a frequency of generally less than 50 percent along the Atlantic east coast littoral (Figure 3). The westward decrease in occurrence is rapid, so much so

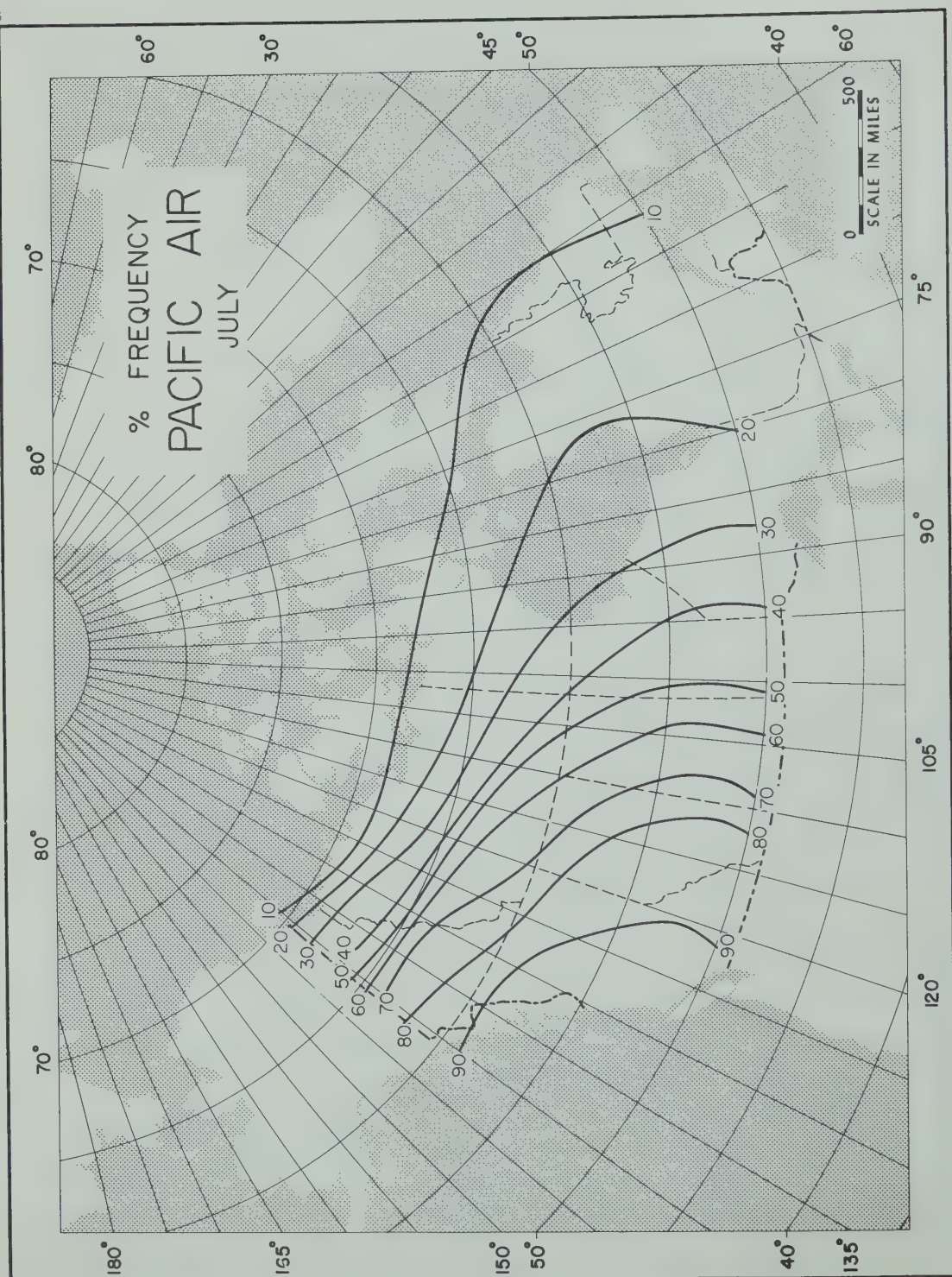


Figure 2. Isopleths of the percentage frequency of occurrence of Pacific air over Canada in July, determined by the trajectory method.

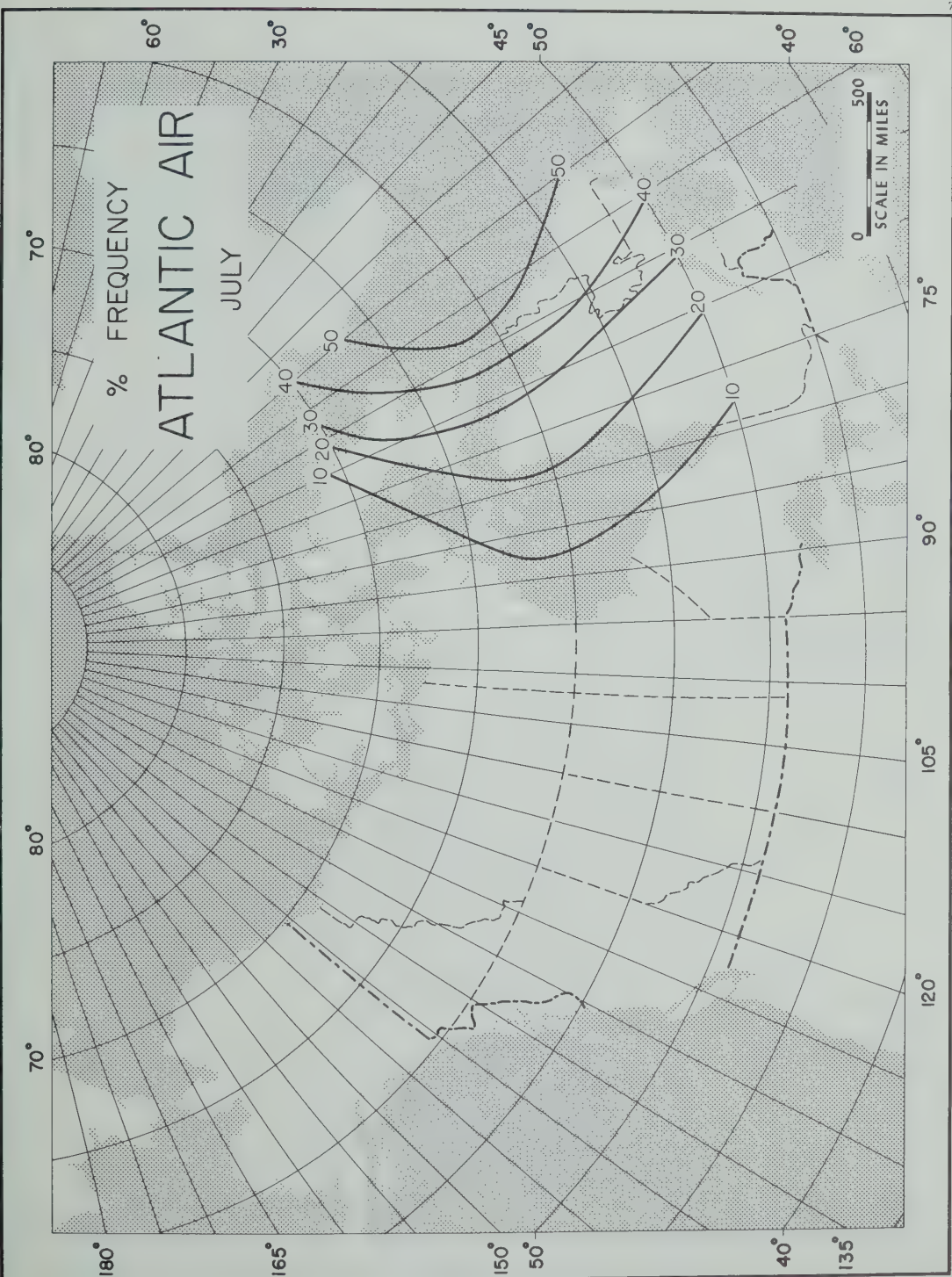


Figure 3. Isoplets of the percentage frequency of occurrence of Atlantic air over Canada in July, determined by the trajectory method.

that the eastern shore of Hudson Bay receives Atlantic air with a frequency of only 20 percent. In contrast, the penetration of Pacific air, favored by the strong zonal westerly flow, is such that along the eastern shore of the Bay, some 2500 miles from its source, it occurs with a frequency equal to that of air from the Atlantic, only 700 miles from its source.

Air which has its origin over or beyond the continental United States, finds a major entry into Canada in the Great Lakes and Plains areas. (Figure 4) South of Hudson Bay the air on one-third of the days in July is of "U.S." origin. This lobe of air which spreads into Canada from the U.S. does not extend over a large area of Canada, but is confined to the region south and east of the Bay. The northward penetration of "U.S." air is considerably reduced west of Hudson Bay. In northern Saskatchewan, for example, "U.S." air appears with a frequency of only 10 percent, and this is largely of Pacific origin ultimately.

Air with a long residence time in a Canadian anticyclone is uncommon in July, reaching a peak frequency of somewhat over ten percent in the Hudson Bay area. (Figure 5)

These charts directly contradict the results of Brunnenschweiler (1952 op. cit.) and Haurwitz and Austin (1944) in that they indicate that unless both Pacific and Arctic air are called cP there is no part of Canada dominated by cP air in July. Relatively moist, cold air from the Arctic dominates the region north of the front delineated by Reed (op. cit.) but this could hardly be called continental. It would appear that the primary source of disagreement is in identification of the air of Pacific origin. It enters the west coast of Canada as maritime Polar air, but east of the Rocky Mountains it is dry and warm by Canadian comparisons although cool by U.S. standards. It appears that this Pacific air, modified, is often called cP.

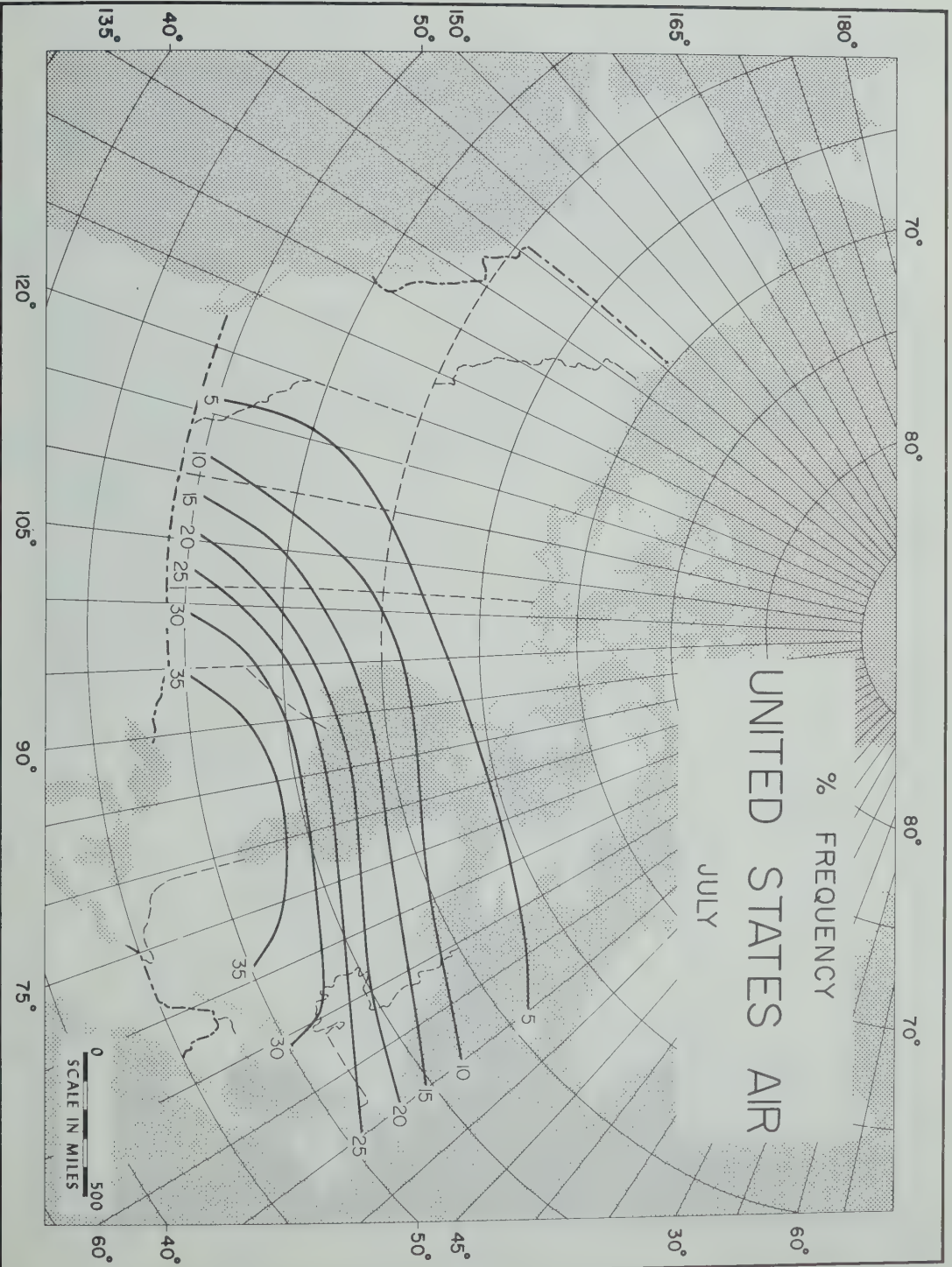


Figure 4. Isopleths of the percentage frequency of occurrence of air which entered Canada from south of the Canada-United States border in July, determined by the trajectory method.

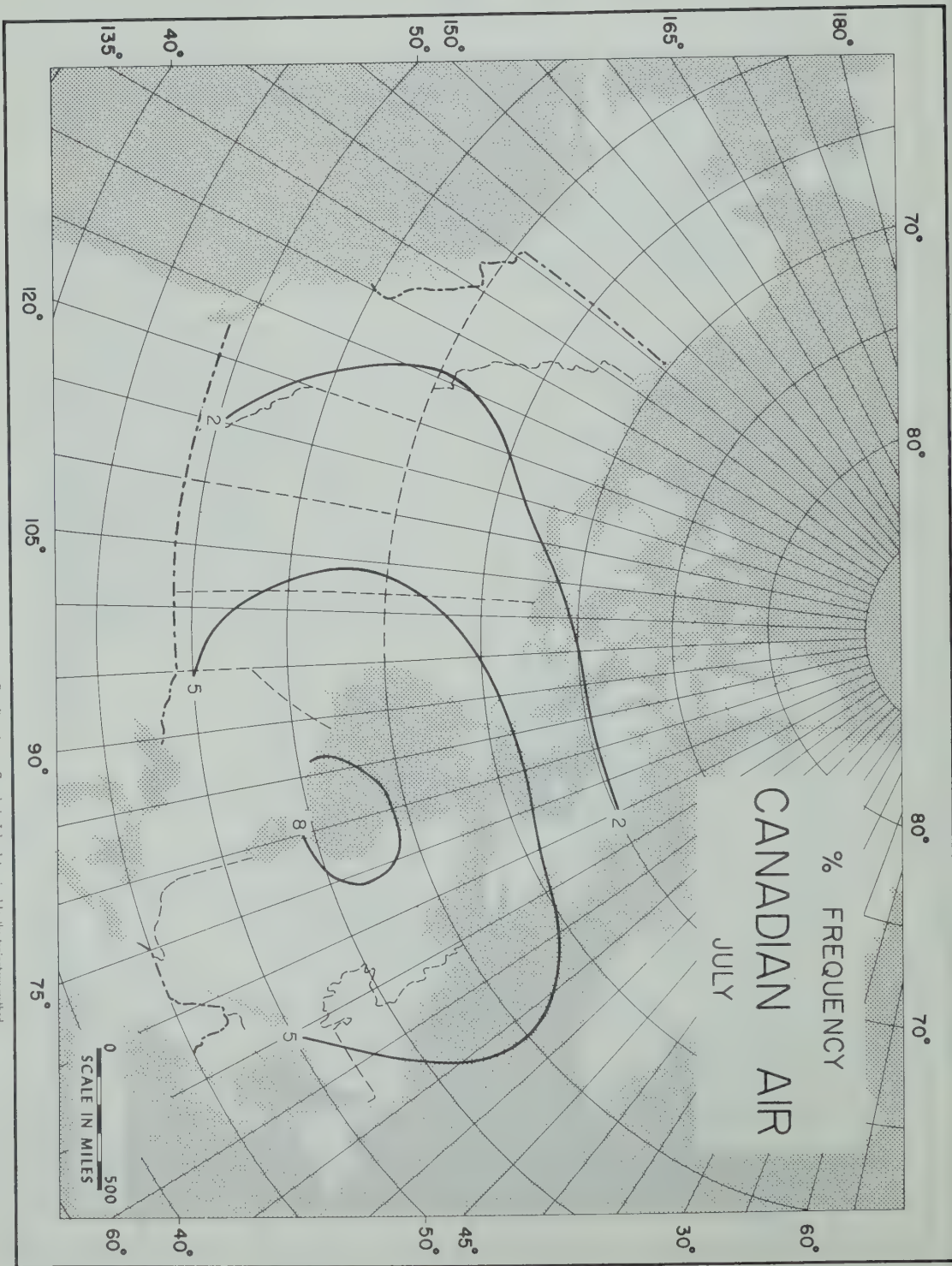


Figure 5. Isopleths of the percentage frequency of occurrence of Hudson Bay or true Canadian air over Canada in July, determined by the trajectory method.

This is an acceptable convention as long as there is no implication of a true anticyclonic source region and long residence time over the continental interior. In this study it shall be called Pacific air.

Examination of figures 1-5 reveals that in north-central Canada there are basically two airmasses present in July, Arctic and Pacific. If the region of equal frequency of these two airmasses is regarded as the modal position of the front between Arctic and Pacific air, one finds that this frontal zone coincides quite closely with the forest border and with the frontal position given by Reed (op. cit.). The northern forest border in central Canada is also the modal position of the front between Arctic and Pacific Air. (Figure 6)

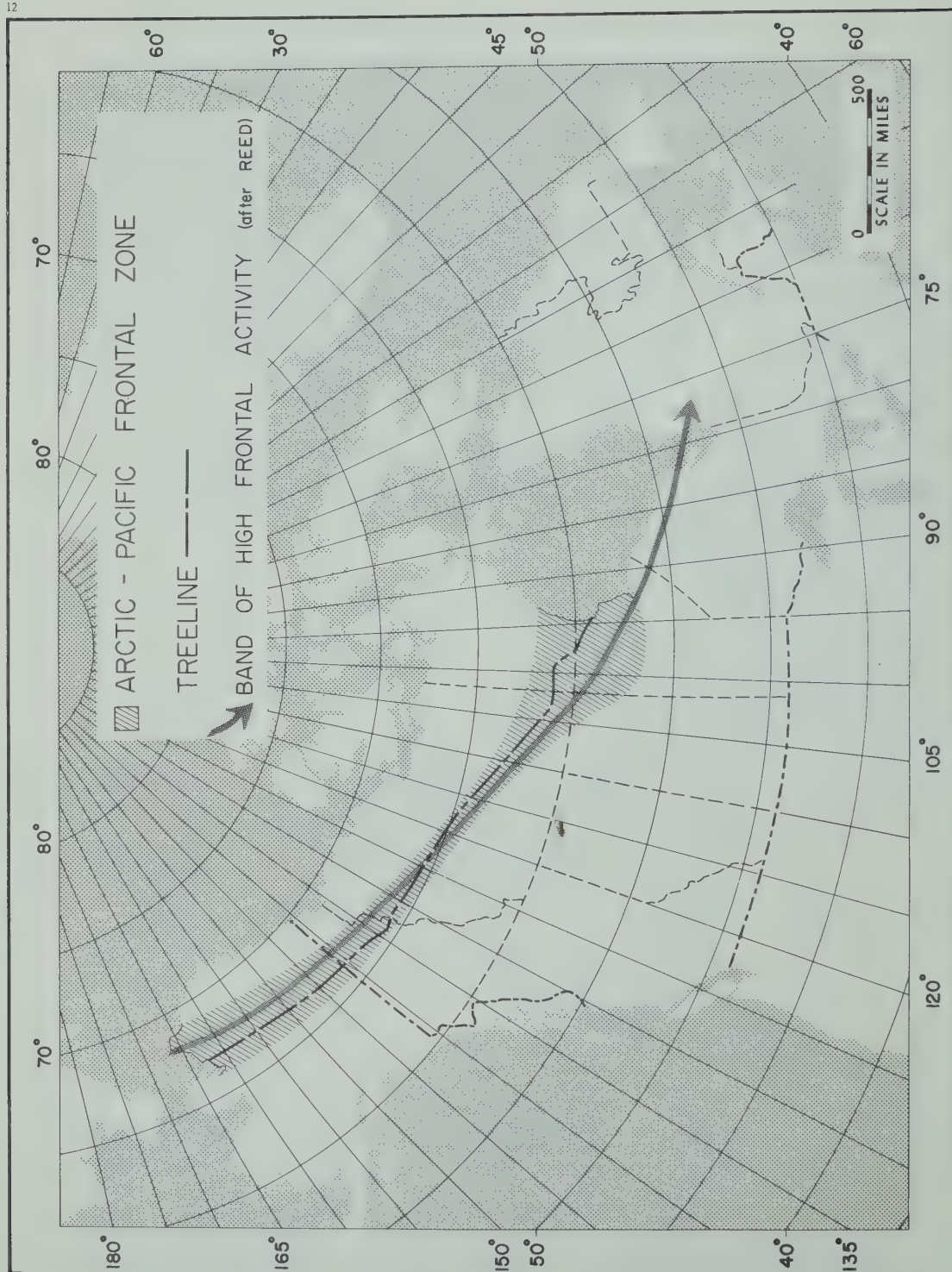


Figure 6. Comparison of the modal frontal zone in July, derived from trajectory analysis of air masses, with the position of the forest border and the summer frontal position given by Reed (1955).

3. AIRMASS FREQUENCY ANALYSIS BY THE PARTIAL COLLECTIVE METHOD

3.1 Multimodal Distributions and Partial Collectives

It is implicit in the air mass concept that different sources produce air of different mean characteristics, with relatively small scatter about these means. Without this assumption the air-mass concept breaks down and air-mass classification becomes arbitrary. Essenwanger (1954) has demonstrated that the frequency distribution of surface temperatures may be decomposed into partial collectives (constituent distributions) which represent individual air masses. An abbreviated version of his method was applied to the frequency distributions of July daily maximum temperatures at about 120 Canadian and U. S. stations for the ten year period 1948 through 1957. Maximum temperatures were taken as being fairly representative of an air mass (Peterssen 1940). The number of stations provided an adequate sample to test the validity and usefulness of the method, and the time period coincides fairly closely with the 10 year period of trajectory analysis so as to provide a basis for comparison of the results of the two methods. For each station, the percentage frequency of occurrence of temperatures within 2-degree categories were calculated. The data was subsequently subjected to a filter function of the form $b' = 0.25a + 0.50b + 0.25c$ and then plotted in the form of frequency curves. The filter function was decided upon subjectively by experimentation with the data. Winter curves were found to be generally much more complicated than summer curves. For summer in Canada a period of 5 years would probably be adequate for this kind of analysis.

3.2 Reduction to Partial Collectives

The frequency curves so constructed appear to be comprised of a series of normal curves. The method employed here for their analysis is a modification and simplification

of that used by Essenwanger.*

The analysis proceeds as follows. First it is assumed that the frequency curve is made up of a series of normal curves. The approximate validity of this assumption has been checked by constructing the frequency distribution of maximum temperature for single airmasses identified by the trajectory method. To separate the normal curves, the first step is to inspect the frequency curve and select the most prominent peaks to which a normal curve might be fitted.

To fit a normal curve to selected peaks, an attempt is made to find peaks whose adjoining partial collectives do not overlap the central section or end peaks which are more than half uncontaminated by the next partial collective (Figure 7). A half uncontaminated end collective may be simply folded along the median ordinate, the resulting symmetrical curve subtracted from the total distribution, and then the analysis continued on the residue. An uncontaminated central portion of a collective will be symmetrical about the mode. Comparison of the ordinates one unit above and below the mode with the modal ordinate and reference to a table of normal ordinates will yield an estimated standard deviation and reconstruction of the partial collective can follow. A second check on the standard deviation often can be made using the ordinate two units away from the mode on the least contaminated side.

Once the partial collectives have been determined, the percentage of the total represented by each may be determined by planimentering.

A second method for reducing the frequency distribution to partial collectives first involves drawing families

* A machine method has been developed for least squares fitting of a series of normal distributions to the total frequency distribution (see Appendix). This method was not available at the time the research for this paper was done.

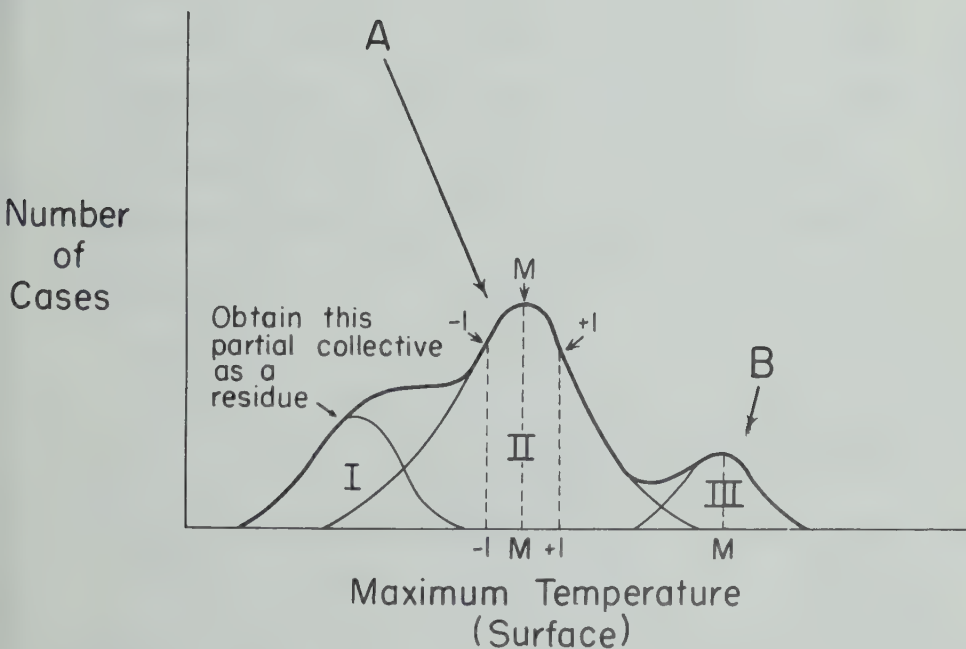


Figure 7. Schematic multimodal distribution illustrating two approximate methods for resolution into partial collectives. The heavy line indicates the total distribution, the light lines indicate reconstructed partial collectives.

Method A—Observe median ordinate, express ordinates one unit above and below the median as a fraction of the median, calculate the standard deviation from tables and reconstruct the partial collective.

Method B—For end collectives, fold the distribution along the median ordinate and subtract from total distribution.

of normal distributions of many different standard deviations and modal ordinates. The appropriate curve may then be selected by superposing the frequency distribution plot over the normal curve families on a light table. Neither method is absolutely accurate, nor as precise as the original Essenganger method (op. cit.) but probably give magnitudes within a few percent of the true value.

3.3 The Validity of the Partial Collective Analysis

A test of the validity of the assumption that these partial collectives represent airmasses may be made by comparing the frequency of an airmass obtained by the trajectory method with the independent value obtained from the partial collective method. Before this can be done, the identification of each partial collective must be made. This is most readily accomplished by making the reasonable assumption that an airmass is most frequent in its source region, and decreases in importance with distance from the source. Thus, when partial collectives are followed from station to station away from the source, changes in frequency and temperature modification are usually sufficiently small so that the identity of the particular collective is preserved. The distribution of airmass frequencies obtained by the partial collective method is compared with the frequencies obtained by the trajectory method in Table I. In general the values obtained by the two methods are in agreement, though some large discrepancies are evident. One would not expect perfect agreement, however, for the periods of time considered are not identical - four years out of ten not being common to the two analyses. Another source of discrepancy lies in the fact that trajectories were computed for $5^{\circ} \times 5^{\circ}$ latitude-longitude "squares" and rather smooth isopleth patterns drawn, from which the station values for Table I were interpolated. In regions of strong air mass frequency gradient these interpolated values may be in error by 30%. The trajectory method is sufficiently accurate to

TABLE I

Comparison of airmass frequencies obtained by the partial collective method with those obtained by the trajectory method

| <u>Station</u> | <u>Arctic</u> | | <u>Pacific</u> | | <u>Atlantic</u> | | <u>U.S.</u> | |
|---------------------|---------------|-------|----------------|-------|-----------------|-------|-------------|-------|
| | PC | Traj. | PC | Traj. | PC | Traj. | PC | Traj. |
| Mould Bay, N.W.T. | 94 | 95 | 5 | ~5 | 0 | 0 | 0 | 0 |
| Cambridge, N.W.T. | 78 | 80 | 23 | 15 | 0 | 0 | 0 | 0 |
| Baker Lake, N.W.T. | 65 | 60 | 34 | 25 | 0 | <5 | 0 | 5 |
| Calgary, Alta. | 2 | <5 | 83 | 83 | 0 | 0 | 13 | 7 |
| Island Falls, Sask. | 32 | 25 | 59 | 50 | 0 | <5 | 8 | 15 |
| Kapuskasing, Ont. | 25 | 10+ | 48 | 25 | 0 | <5 | 22 | >35 |
| Knob Lake, Labr. | 35 | 20 | 32 | 15 | 24 | 35 | 7 | 20 |
| Regina, Sask. | 3 | <10 | 71 | 60 | 0 | 0 | 26 | 23 |
| Maniwaki, Que. | 9 | <10 | 51 | 15 | 3 | <10 | 36 | >35 |

| | <u>Pacific & U.S.</u> | | <u>Arctic & Atlantic</u> | |
|--------------|---------------------------|-------|------------------------------|-------|
| | PC | Traj. | PC | Traj. |
| Calgary | 96 | 90 | 2 | <5 |
| Regina | 97 | 83 | 3 | <10 |
| Maniwaki | 87 | >50 | 12 | <20 |
| Island Falls | 68 | 65 | 32 | 30 |
| Kapuskasing | 60 | >60 | 25 | 15 |
| Knob Lake | 39 | 35 | 59 | 55 |
| Baker Lake | 34 | 30 | 65 | 65 |
| Cambridge | 22 | 15 | 78 | 80 |
| Mould Bay | 5 | 5 | 94 | 95 |

provide a reasonably certain identification of the general airmass distribution pattern, and the partial collective method is sufficiently sensitive to give details.*

Some features of analysis by this method are illustrated by several profiles which extend from source regions into areas of considerable airmass heterogeneity.

Maritime tropical air entering the Gulf Coast of the United States is quite homogeneous and in places like Brownsville, Texas and Burrwood, Louisiana where the winds are onshore nearly all summer it should be present nearly 100% of the time. Thus one partial collective should be present with a modal temperature characteristic of mT air and a magnitude of about 100%. Farther inland (northward) various other varieties of air should become increasingly important and the magnitude of the mT collective should decline. This change in relative importance is quite clear in the array of collectives versus temperature shown in Figure 8. In this figure the modal temperature of each collective is arrayed on the abscissa and the latitude on the ordinate. The percentage of the total for each partial collective is given at its modal temperature.

At Brownsville, Texas, only one collective is present, and it represents the maritime Tropical air which is present throughout July. Moving farther north, Houston, Texas, has other than typical mT air present 11% of the time, but mT air continues to dominate and exists at about the same temperature as at Brownsville. Tropical air appears to be less common at Little Rock, Arkansas (70%) but it is warmer in mid-day than on the coast. It would appear that

* A check on the validity of the graphical analysis of the frequency distributions may be made by comparing the results with those obtained by least squares computer fitting of a series of normal distributions (see Appendix).

the lower mean July maximum at Little Rock than at Houston is due to the cooler varieties of air which are more frequent at Little Rock.

This concept may be tested by comparing cool Julys at Madison, Wisconsin with warm Julys at the same station (Table II).

TABLE II

Comparison of partial collectives for below normal Julys with those for above normal Julys, Madison, Wisconsin

| | | | | | | | | | | |
|------------------|------|----|------|----|----|------|----|----|------|-----|
| Modal Temp °F | 64.5 | 70 | 75.5 | 80 | 82 | 86.5 | 87 | 92 | 95.5 | 100 |
| % in Cold | 2 | 8 | 21 | 34 | | 29 | | 4 | 1 | 1 |
| % in Warm | 0 | 0 | 15 | | 32 | | 31 | 12 | 6 | 3 |

In only two cases do the collectives from the two independent halves of the sample have as much as two degrees modal temperature difference. The outstanding difference between warm July months and cold ones lies in the difference in frequency of the various types of air. This may be seen even in the gross features of the total distribution curves (Figure 9), the same peaks appearing on independent sets of data sorted by overall character of the month, but with differing frequency.

The appearance of all partial collectives increasing in modal temperature northward through the United States (Figure 8) is in part real and in part an artifact due to the reduction of temperatures to sea level using 3.3°F per 1000 ft. In part the difference is due to the two hours longer day and shorter night in the Dakotas compared to the Gulf Coast, and in part it may be because only the more extreme outbreaks of colder air reach the southern stations. In Canada the partial collectives show rather uniform warming southward.

Moving from south to north, one sees that types of air other than maritime Tropical appear and increase in

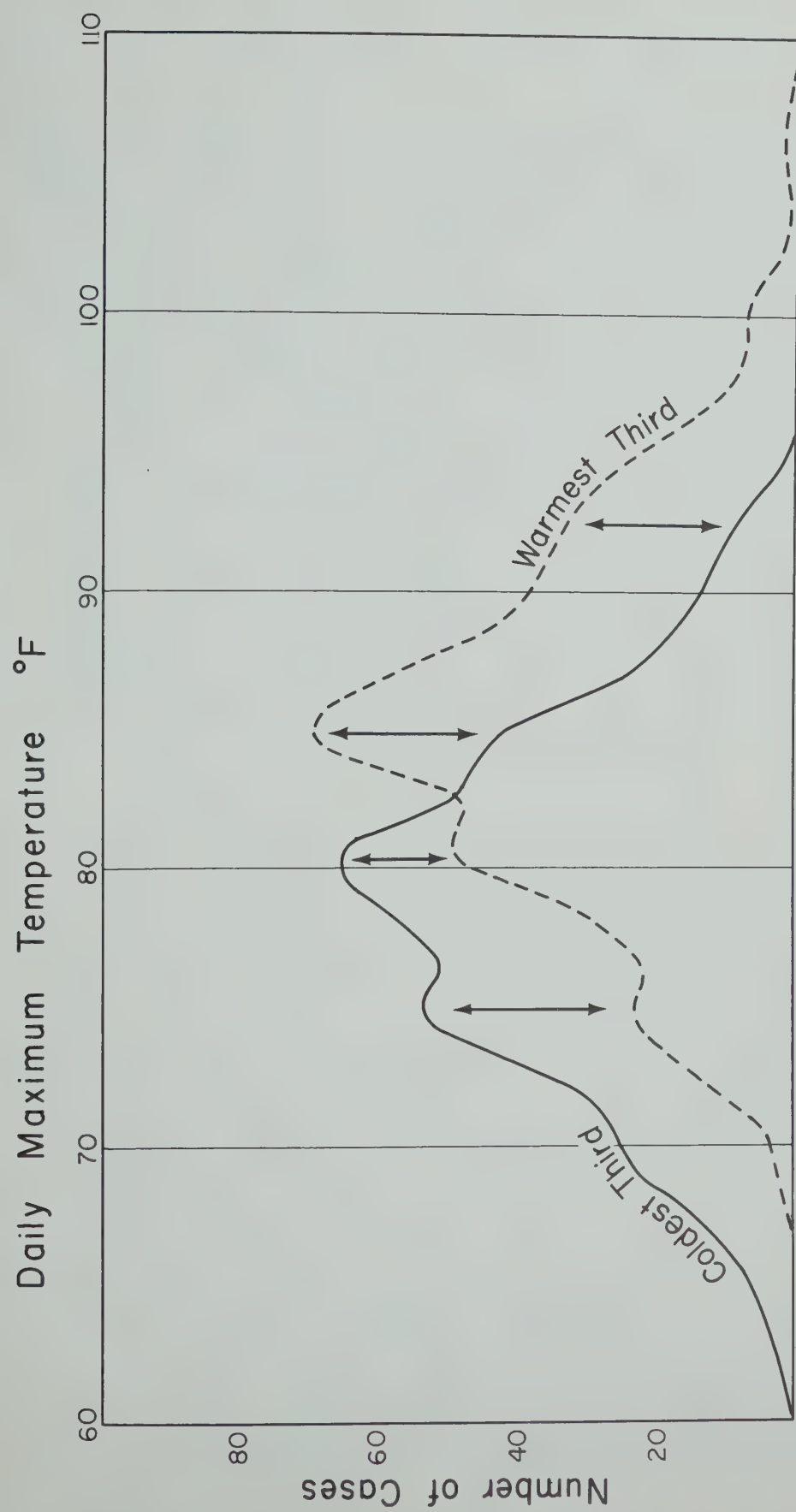


Figure 9. Frequency distributions of daily maximum temperature at Madison, Wisconsin in July with mean monthly temperature in warmest third of all cases on record and in coldest third. The same peaks appear in the two completely independent sets of data.

importance in rather regular fashion to a latitude of maximum frequency. Those which reach maximum frequency on the shores of the Arctic Ocean must be regarded as Arctic air by the same reasoning applied above to mT air and its peak frequency on the shores of the Gulf of Mexico. Indeed these particular cold collectives, indicated Aw1 and Aw2 in Figure 8, decrease along all profiles away from the Arctic Ocean. The differentiation into two collectives representing Arctic air at Mould Bay suggests that the colder one, close to freezing, represents air derived directly from over the frozen sea, while the warmer variety has had some trajectory over the land. Farther inland this difference should disappear, and it does in all cases. The two collectives then merge into one. Such merging is not uncommon, as air derived from two nearby but distinctive sources travels farther and farther over similarly modifying terrain. It is quite surprising, in fact, how far the partial collectives maintain their identity.

The region of overlap of two adjacent partial collectives includes, of course, air which is being modified towards the characteristics of the other variety as well as mixtures of the two varieties. Clearly when the overlap reaches some large figure, the varieties can no longer be distinguished.

Examining Figure 9 one notes that one collective reaches a maximum frequency of 41% at Wabowden, Manitoba and is less frequent to the north and south. This can be neither a tropical variety of air nor an Arctic variety. Comparison with stations to the west and east shows that this variety increases in frequency westward, and in fact may be traced to a core of maximum frequency at the base of the Rockies in Alberta. It is thus reasonable to assign a Pacific origin to this collective. (Figure 10) This collective is designated CR in Figures 9 and 10. Following the next cooler collective at Wabowden in the same manner leads to two cores of maximum frequency at the base of the Rockies west of Great

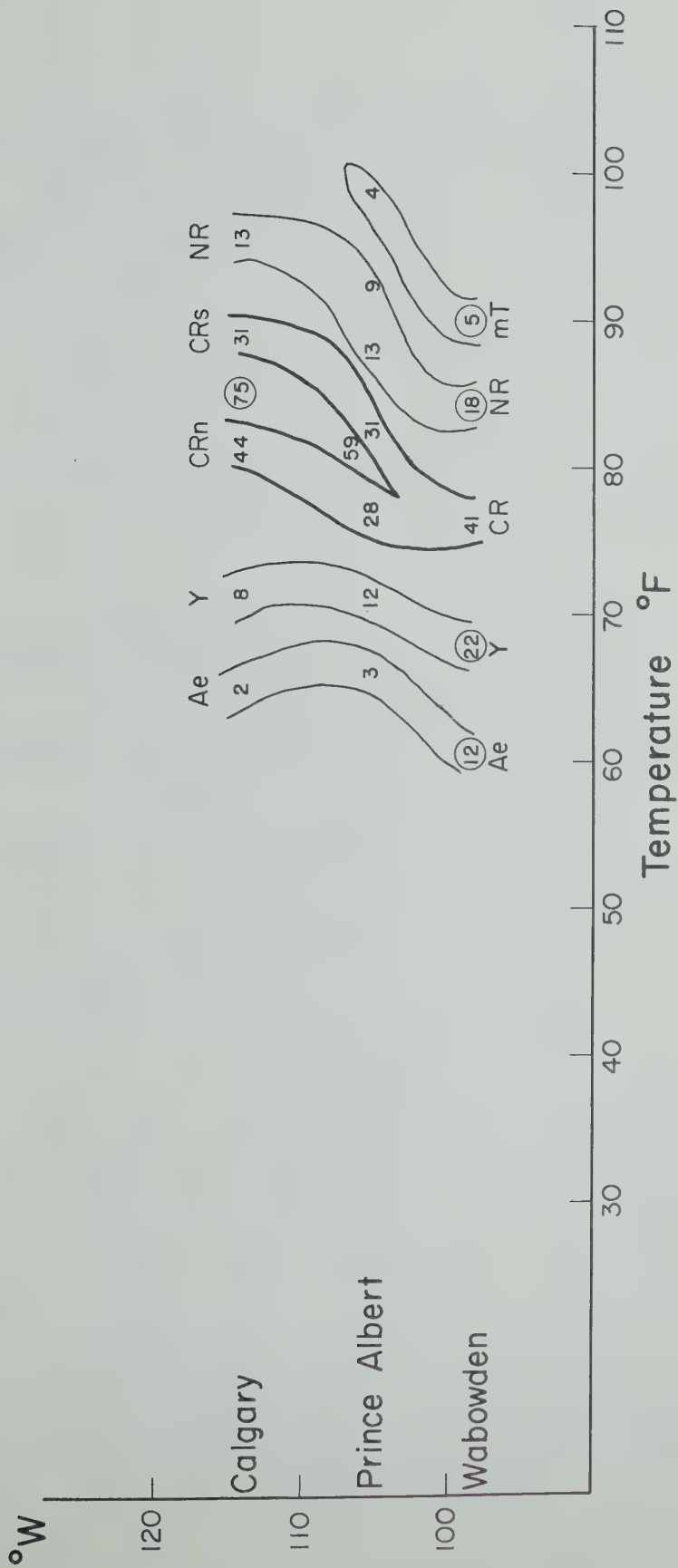


Figure 10. Relative frequency of occurrence of July air masses at Wabowden, Manitoba, Prince Albert, Saskatchewan, and Calgary, Alberta. Conventions as in figure 8. Bold figures between the two CR collectives give the combined frequency of the two sub-types.

Slave Lake, a warmer one apparently representing air crossing the Rockies southwest of Fort Simpson and a cooler one crossing the Rockies southwest of Aklavik (Figure 11). These collectives are designated Y and A1 respectively in the figures.

Similarly, the other collectives in Figures 8, 10 and 11 can be traced to core regions which identify the source of the air. In Table III the various sources and designations are summarized.

TABLE III

Source regions for air represented by partial collectives - and designations used in this paper

| <u>Abbr.</u> | <u>Name</u> | <u>Remarks</u> |
|--------------|--------------------------|---|
| cT | continental Tropical | Hot, enters eastern North America around southern end of Southern Rockies and out of Mexico |
| mT | maritime Tropical | Standard definition, mostly from Gulf of Mexico |
| NR | Northern Rockies Pacific | Crosses the Rockies in Montana and through the Wyoming gap |
| Y | Yukon Pacific | Crosses the Rockies through the Liard River gap |
| A1 | Alaskan | Enters the Mackenzie Valley from Alaska, apparently through the Pelly and Peel Valleys |
| Ae | Eastern Arctic | Develops over the Arctic Archipelago |
| Aw | Western Arctic | Develops over the Arctic Ocean Aw1 direct from sea Aw2 with land trajectory |
| HB | Hudson Bay | Air of diverse origins with long residence time over Hudson Bay |
| Atl | Atlantic | Maritime air, cold, entering Canada from the Labrador coast or Baffin Bay |
| CR | Canadian Rockies Pacific | Crosses the Rockies into Alberta, especially in the Edmonton-Calgary area |

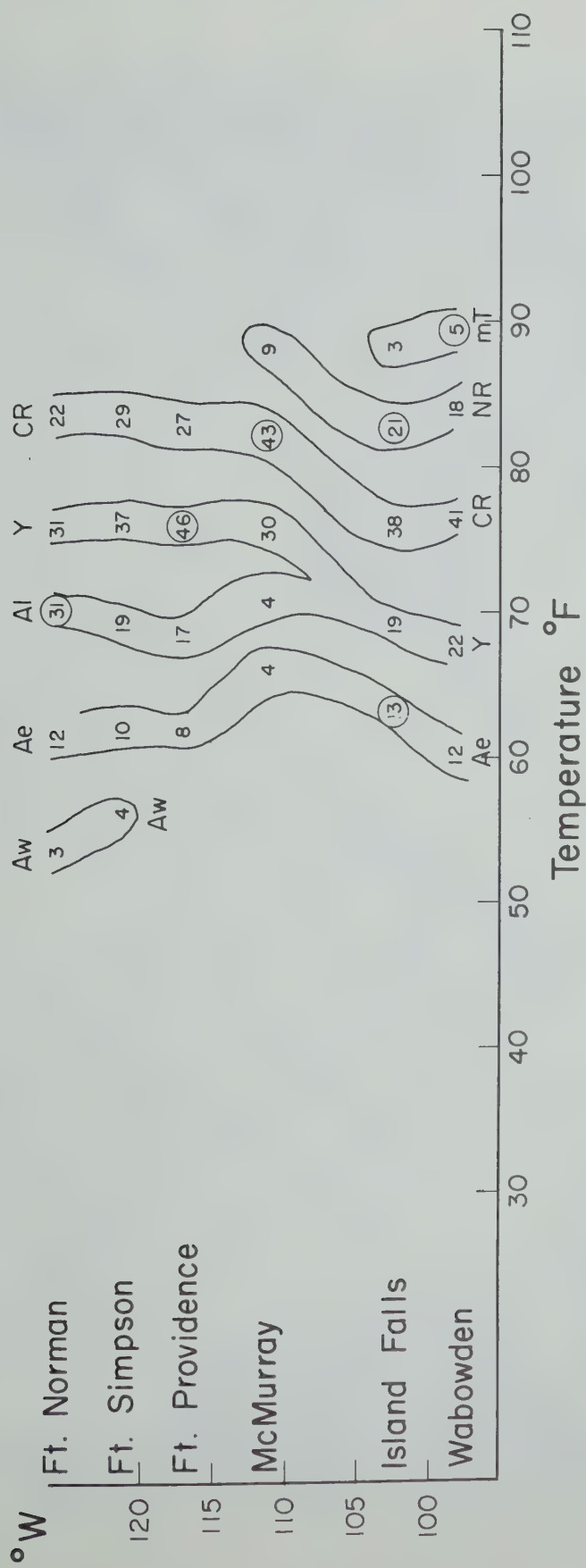


Figure 11. Relative frequency of occurrence of July air masses along a profile northward from Wabowden, Manitoba. Conventions as in figure 8.

3.4 The Distribution of Airmasses determined by the Partial Collective Method

Breaking down the frequency distribution of daily maximum temperatures into partial collectives, station by station, and tracing each collective to its core of maximum frequency (origin), it is then possible to map the frequency of occurrence of the various air masses. There are, obviously, many pitfalls in tracing the partial collectives from one station to another, especially in regions of sparse data. However, if the collectives are traced from one station to another some distance away by separate paths of intervening stations and the same correspondence is achieved by these alternate paths, some credibility is lent to the results. Clearly there are a large number of such alternate paths in a continental network, and an internally consistent identification for all stations leaves essentially no alternate solutions. This is especially true if one further requires that each collective diminish regularly in frequency away from its assumed origin, e.g., there can be no isolated maximum of frequency of an individual airmass except in its region of origin.

It is possible, at the cost of considerable time and care, to achieve such an essentially unique solution to the identification of each partial collective. The results of my analysis are summarized in the maps of Figures 12-19, which give the distributions of the major airmasses listed in Table III. These maps may be summarized by drawing on one chart the boundaries of the regions occupied more than 50% of the time in July by a single airmass or group of closely related airmasses (e.g. Aw1 plus Aw2, or Y plus A1). This chart, Figure 19, delineates certain regions which should be compared closely with those derived by a totally independent method in the following chapter (Figure 32).*

* It is clear that use of only the daily maximum temperature cannot give unequivocal airmass identification, but a method for the analysis of multi-parameter frequency distributions is not yet known to the author.

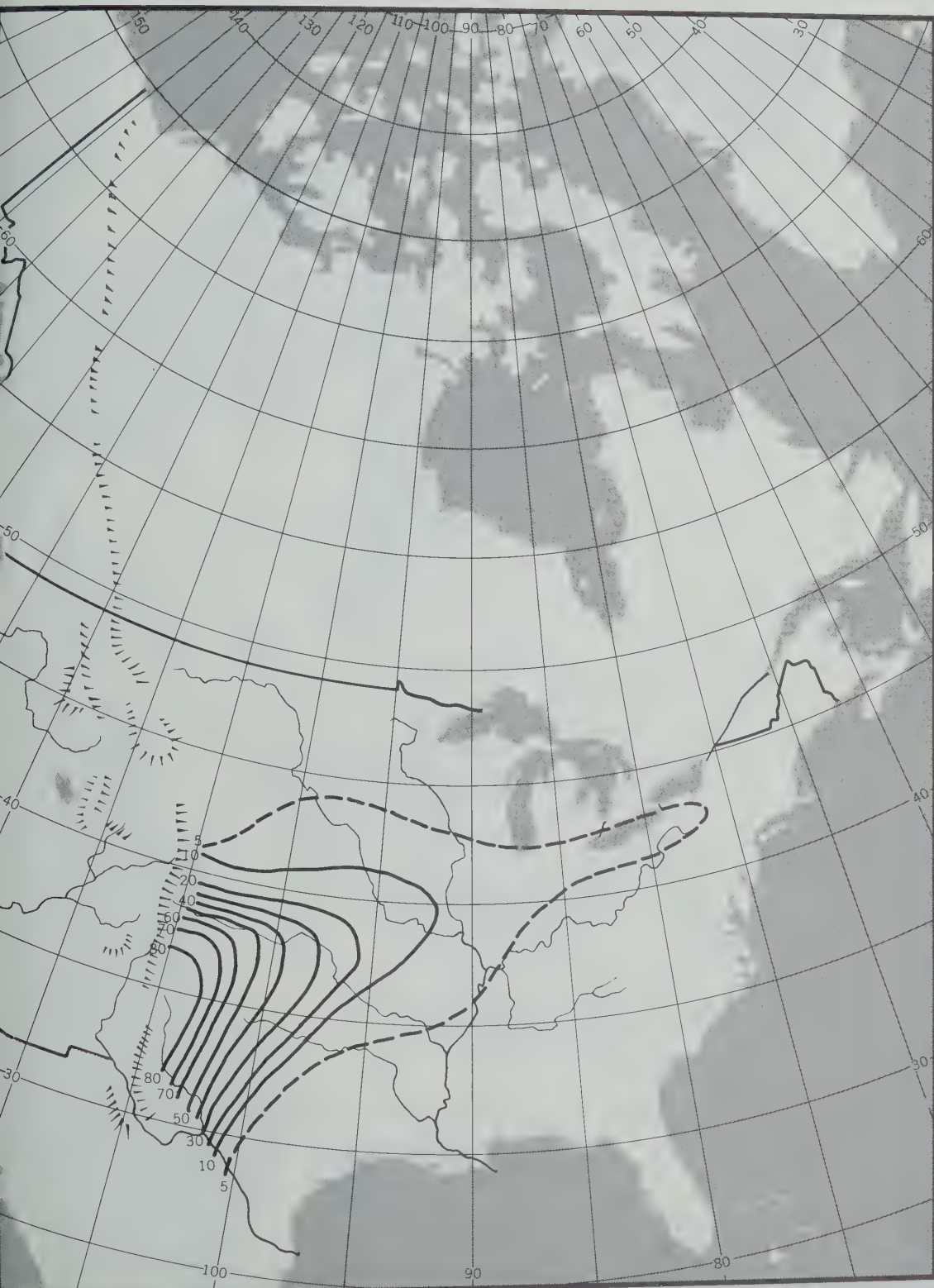


Figure 12. Frequency of occurrence of continental Tropical air east of the Rocky Mountains in July (%).

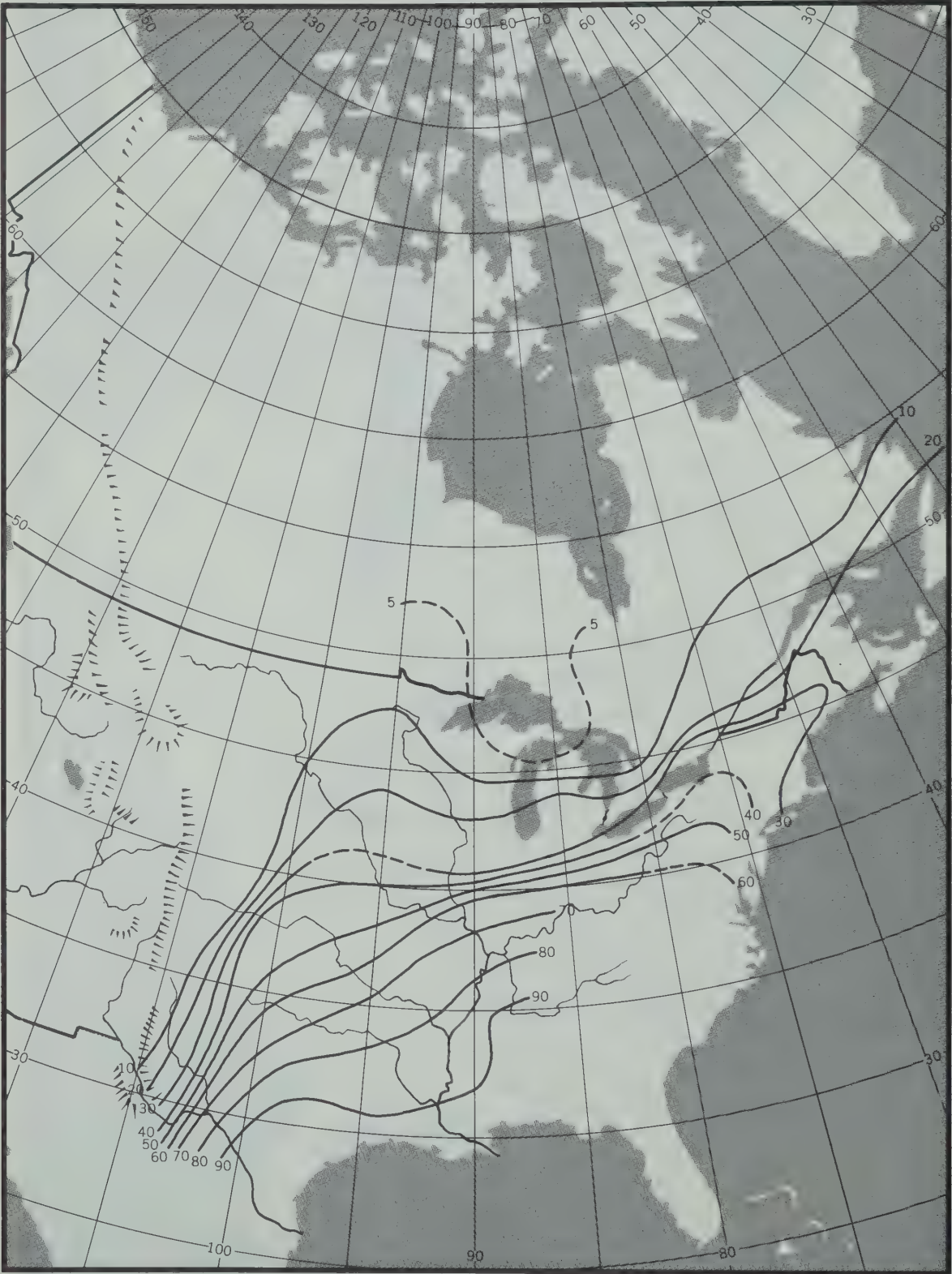


Figure 13. Frequency of occurrence of maritime tropical air east of the Rocky Mountains in July (%).

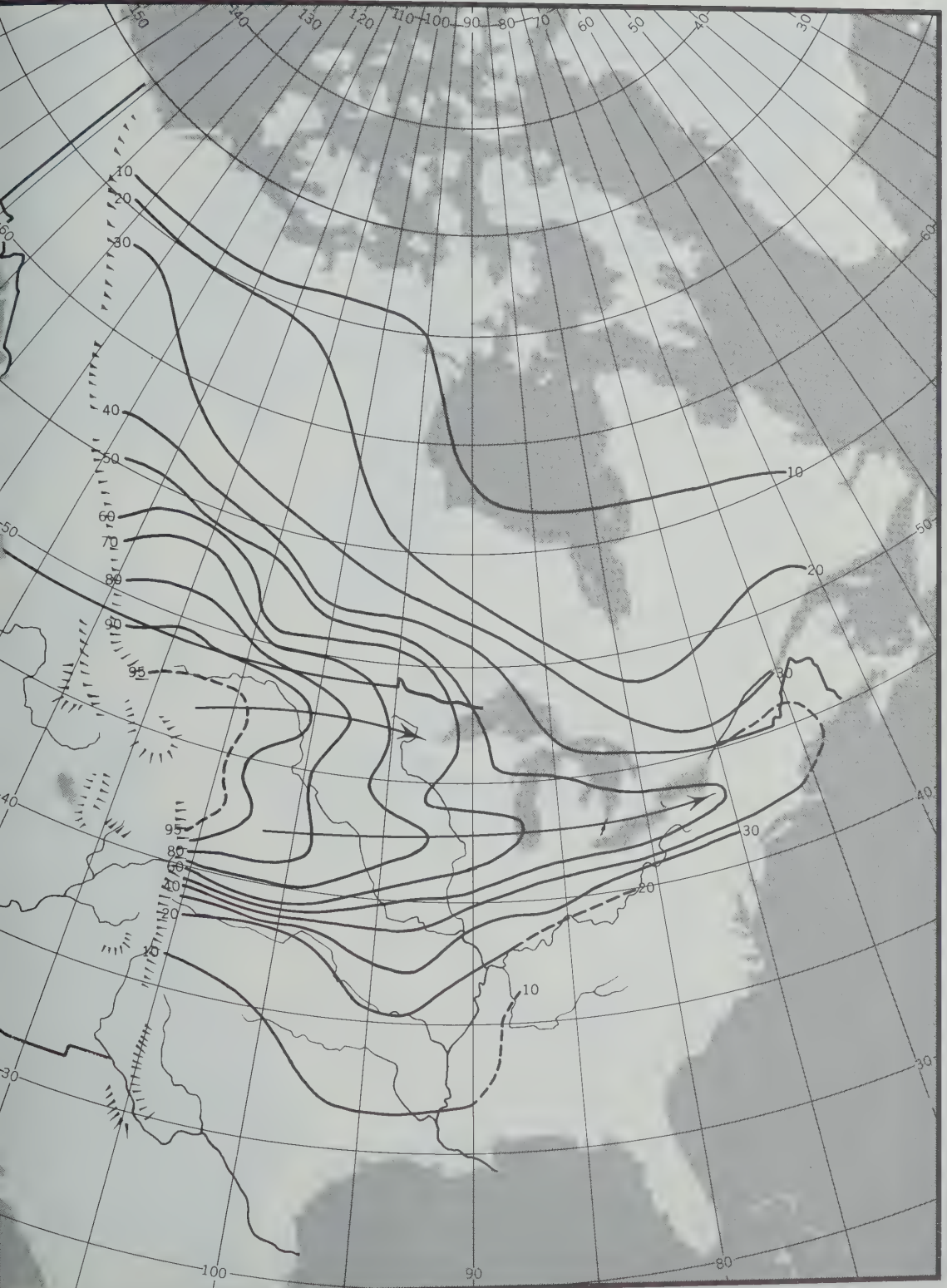


Figure 14. Frequency of occurrence of Pacific air entering the region east of the Rocky Mountains through Wyoming, Montana and Southern Alberta (CR and NR air masses of Table III) in July (%).

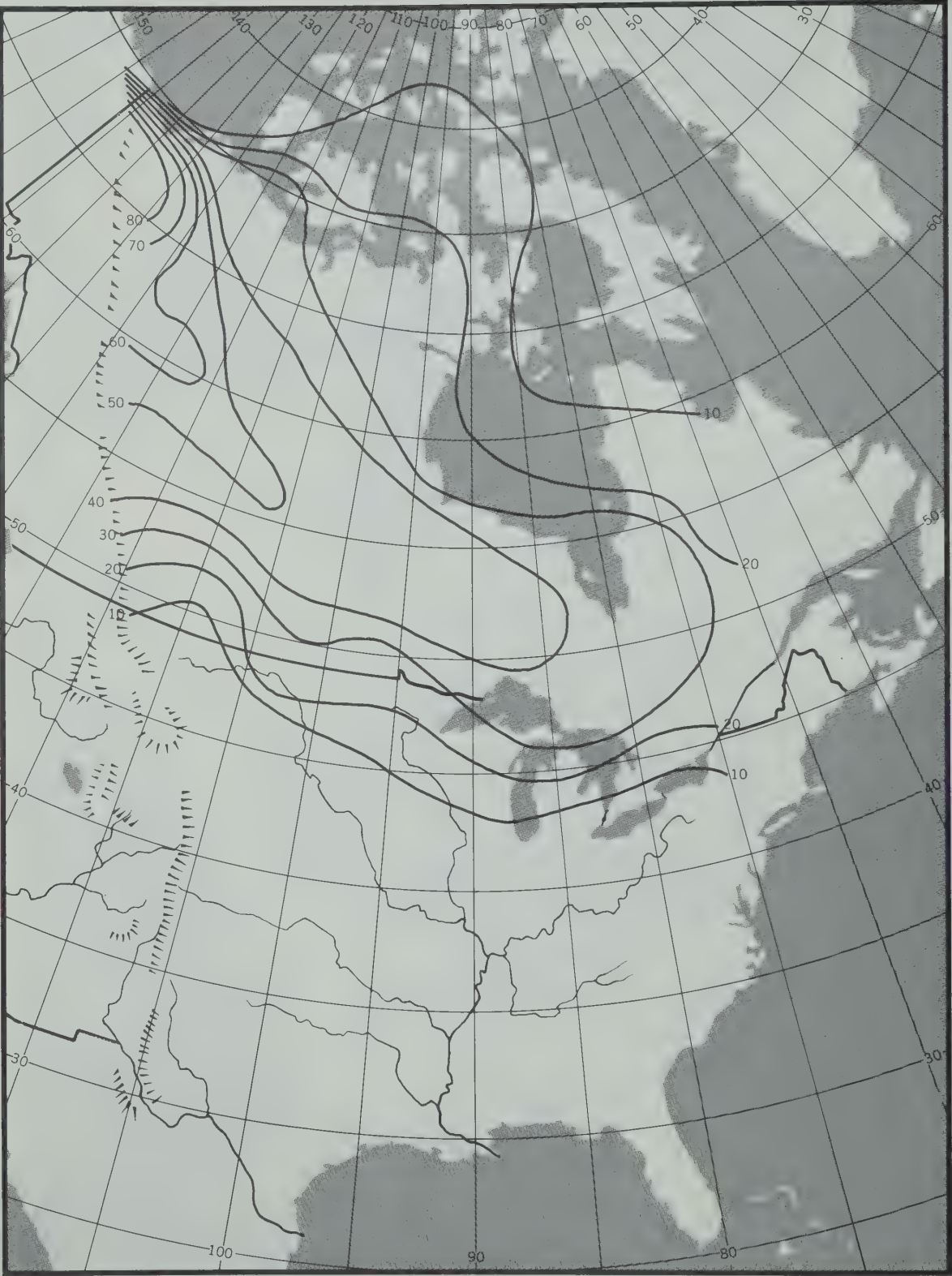


Figure 15. Frequency of occurrence of air which originates west of the Cordillera and enters the region east of the mountains from Alaska and the Yukon Territory (A1 and Y air masses of Table III) in July (%).

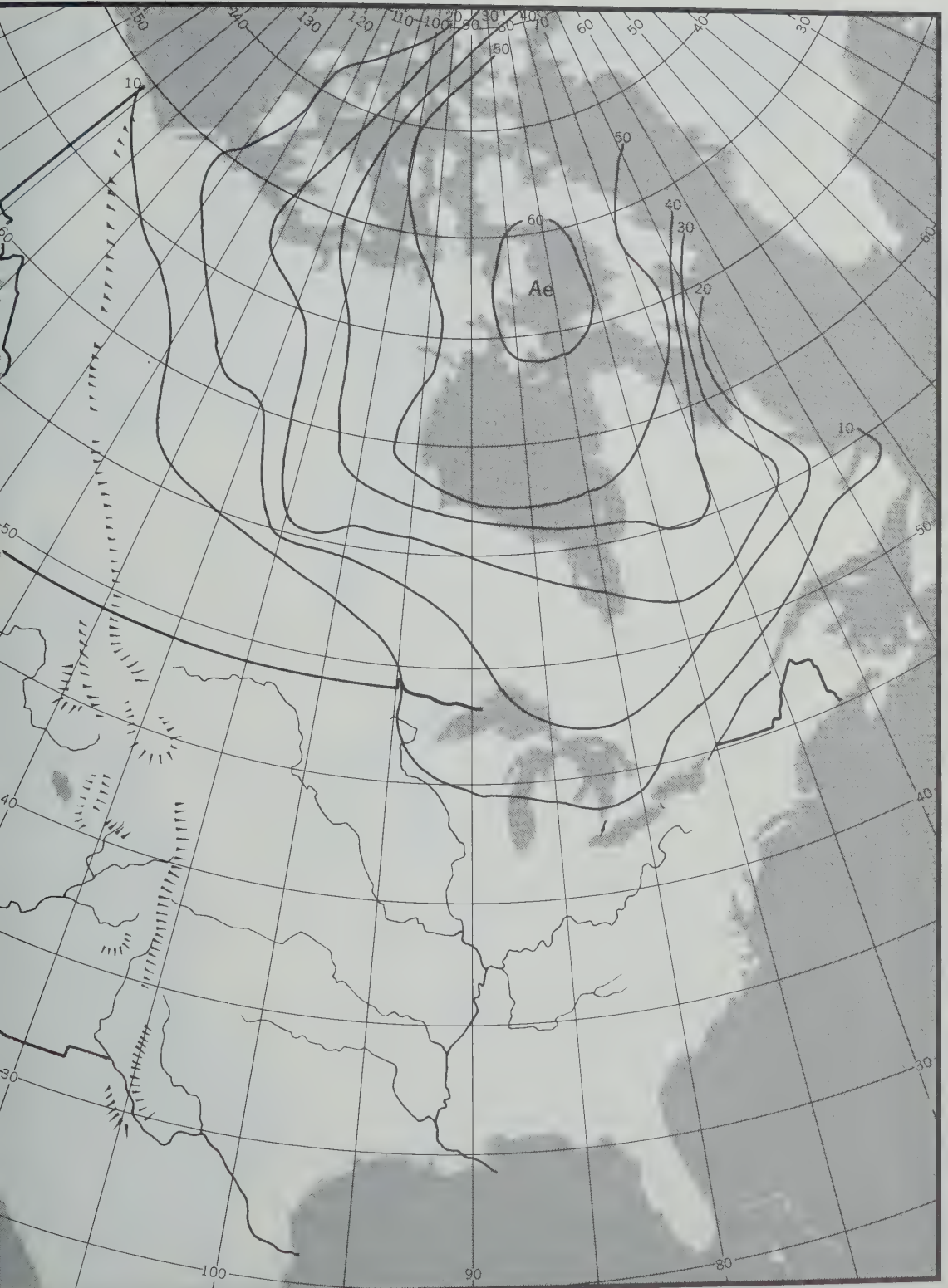


Figure 16. Frequency of occurrence of air masses originating over the Canadian Arctic Archipelago (Ae) in July (%).

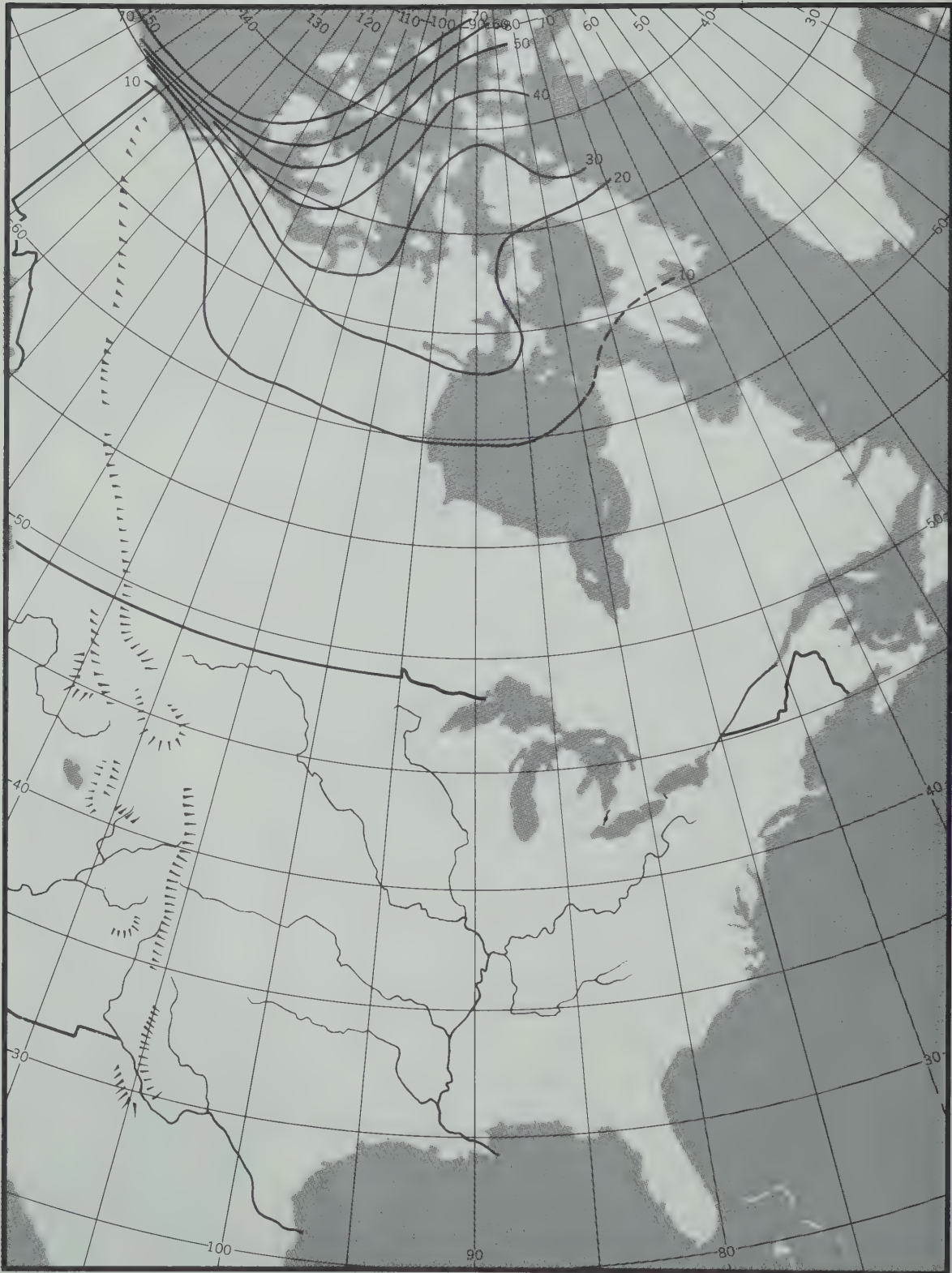


Figure 17. Frequency of occurrence of air masses originating over the Arctic Ocean (Aw) in July (%).

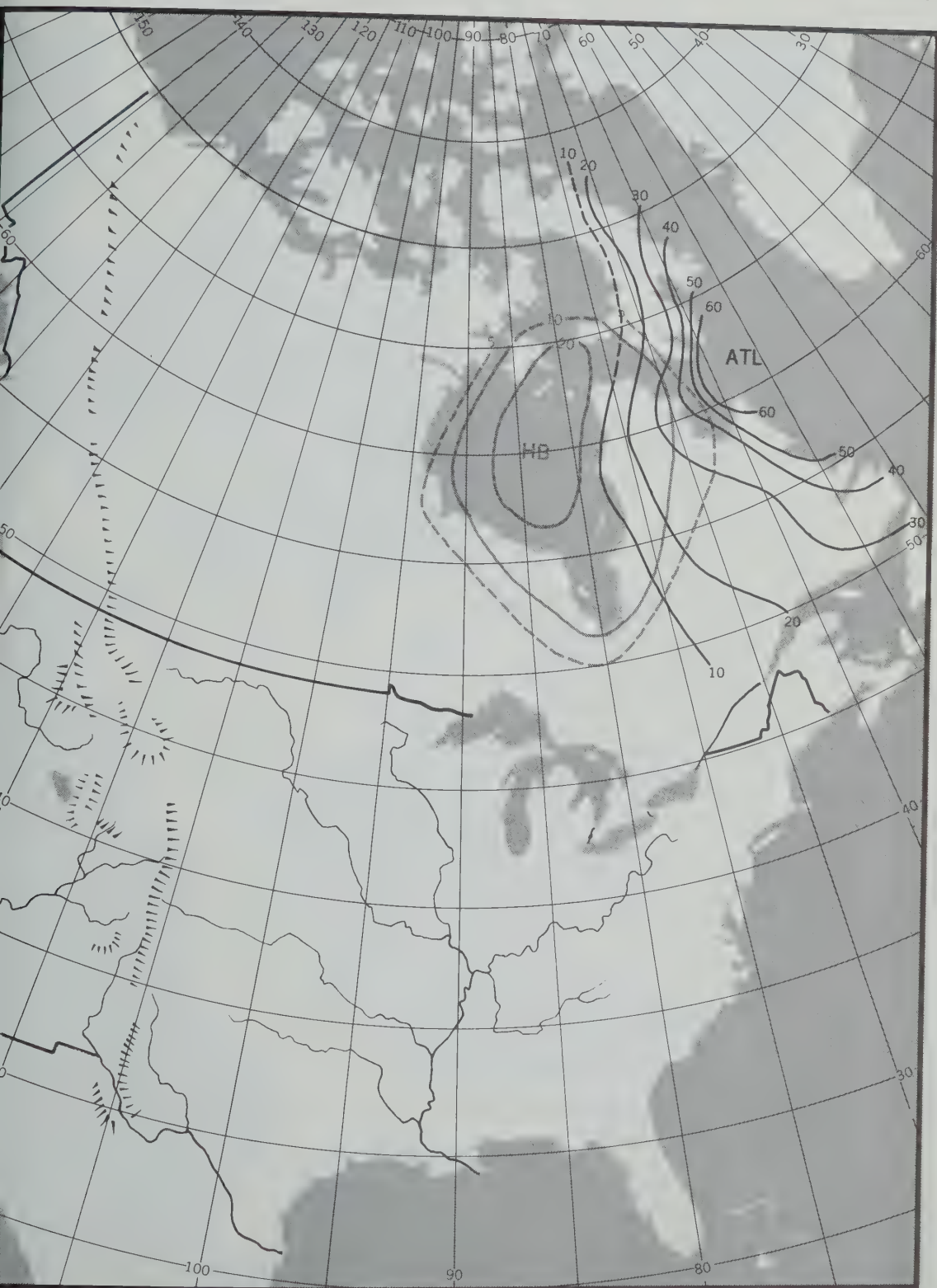


Figure 18. Frequency of occurrence of air masses originating over Hudson Bay (HB) and the North Atlantic (Atl) in July (%).

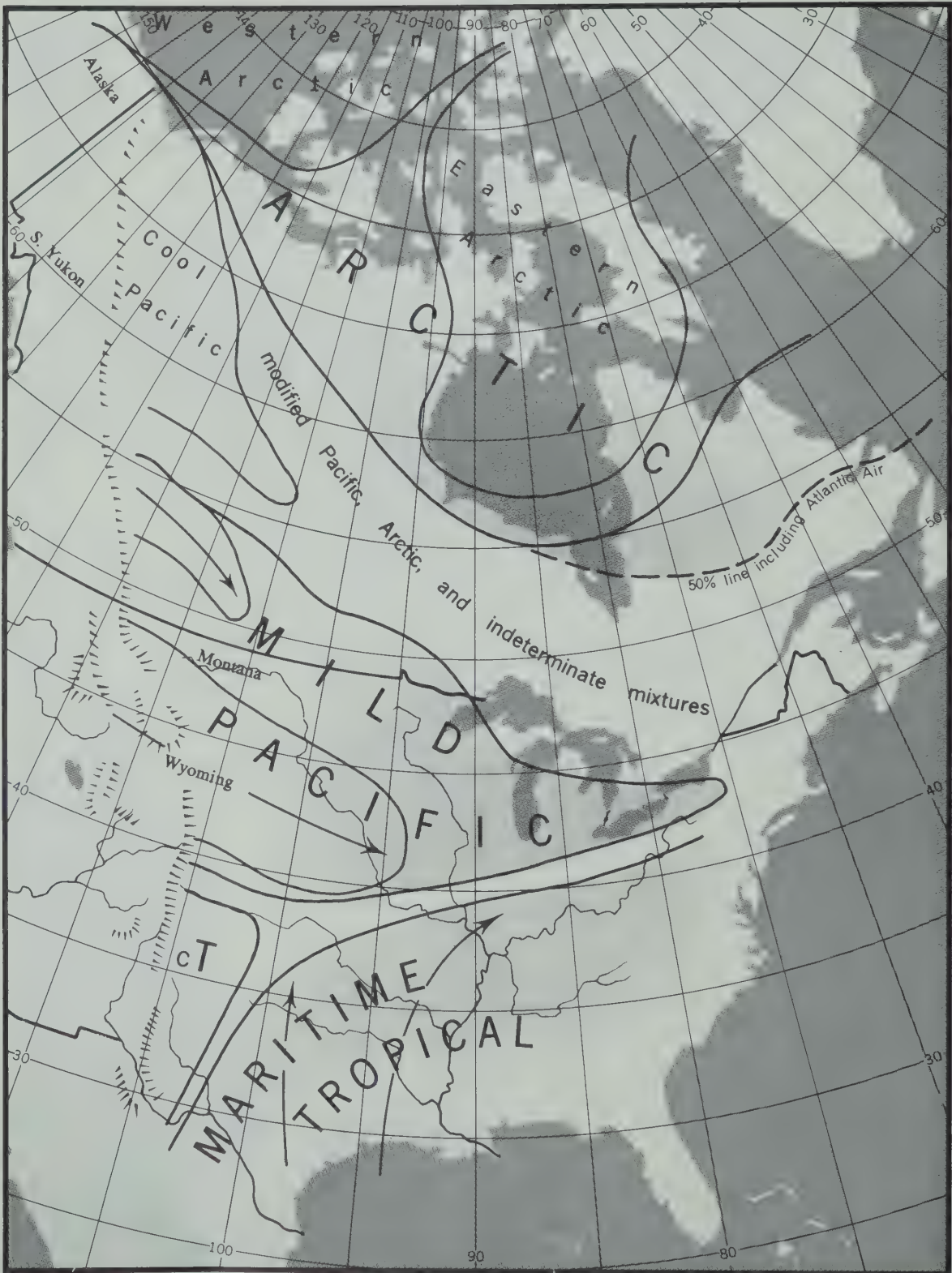


Figure 19. Composite chart of regions dominated by the various air mass types. The shaded regions are occupied more than 50% of the time by the indicated air masses.

3.5 Partial Collective Distribution and the Boreal Forest Boundaries

In the preceding chapter it was shown that the area occupied more than half the time by Arctic air in July (determined by trajectory) lies north of the tree line in Central Canada, and the area occupied by Pacific air on more than half the July days lies south of this biotic boundary. The same is found to be true on the chart derived by the partial collective method, which is based on independent data. This boundary should then be the modal position of the front that normally separates Arctic and Pacific air, or approximately the modal track of wave cyclones which move along that front (Reed, op. cit.). The agreement in position of the tree-line, the storm track, the airmass boundary derived from trajectories, and the airmass boundary derived from the partial collectives of daily maximum temperature is amazingly good. Once again it appears that the northern forest border is also the modal July position of the Arctic Front in Central Canada. The 50% isopleth for Arctic air passes between Fort Reliance and Artillery Lake at the eastern end of Great Slave Lake. The forest border is clearly defined in this region and crosses Artillery Lake about twenty miles from the position of the 50% isopleth. This same isopleth passes about 20 miles south of Ennadai Station in southwestern Keewatin, within five or ten miles of the true position of the forest border as seen in the field. The isopleth cannot reflect the detailed wanderings of the tree-line but approximates the forest border very well from Aklavik to the Atlantic.

The southern edge of the boreal forest also follows quite well the 50% isopleth at the northern edge of the wedge of mild Pacific air which has crossed the Rockies in southern Alberta, Montana and Wyoming. However this reflects only a change in dominance of mild Pacific air versus a cooler variety of Pacific air. This seems to be physically too insignificant to be causally related to the boundary between prairie and spruce forest. This may be a fortuitous

coincidence, but the evidence to be presented in the next chapter suggests that the summer position of the transition in airmass dominance shown in Figure 19 is a reflection of a more significant winter contrast.

4. SURFACE STREAMLINES AND MEAN CONFLUENCES OVER LOWLAND NORTH AMERICA

4.1 Monthly Mean Surface Streamline Charts

In the preceding chapters reference has been made to mean or modal frontal positions implied by narrow zones of transition between regions dominated by differing airmasses. In this chapter we shall try to corroborate the existence and location of these mean fronts by using still a third set of data.

In chapter 2, trajectories were computed to establish the distribution of airmass frequency, and in chapter 3 the distribution of airmass frequencies was determined by analysis of the daily maximum temperature frequencies. Since distinctly different airmasses are normally separated by fronts, it would seem reasonable to look for mean convergences or at least mean confluences in the regions normally occupied by these fronts. On mean charts, mean streamlines are also mean trajectories, so one must expect that the region normally occupied by Arctic air, for example, should be a region of streamlines leading back to the Arctic source region, etc.

If the mean confluences of the airstreams are as sharply defined as implied by the narrow zones of airmass frequency transition, then they should also be sharply defined on resultant wind streamline charts, more so in central Canada and the plains and less so in the east where the airmass analysis is less definitive as the result of extensive modification before arrival.

For our present purpose the resultant winds aloft are available for only a loose network, but over much of North America east of the Rockies there is little relief and the surface resultants should serve. Indeed if significantly pronounced confluences do exist they should be evident in surface winds.

Unfortunately, a homogeneous set of surface resultants for the same period of time as the airmass analyses does not exist. For the United States, resultant winds for the

surface level at pilot balloon stations were available for intervals of five to twenty or so years, mostly in the 1930 decade. For Canada, resultants were reconstructed from tables of wind speed and frequency by direction to eight points at anemometer level. As a check, ten year mean geostrophic winds were calculated at grid intersections over North America, corrected for cross-isobar deviation within the friction layer, and used wherever no other data was available. Resultant surface streamlines were then drawn for each month. These charts are reproduced as Figures 20-31.

The series of streamline charts starts with the pattern for November, for reasons that will soon be obvious (Figure 20). Distinct airstreams are clearly defined on the chart. There is an anticyclonic center located over Alabama and Georgia, the outflow from which flows northward across the south-central states, north-eastward along the Appalachians and eastward to the Atlantic. On the north this airstream meets the southern edge of an airstream flowing eastward from the base of the Rocky Mountains. The former represents a stagnant anticyclone, usually with modifying continental polar or maritime Polar air returning northward ("return Polar"), and the latter a stream of fresh Polar air of originally maritime (Pacific) origin, but modified by its passage across the Rockies. The boundary or confluence between these airstreams lies along a curve from Fort Collins, Colorado through northern Missouri, then through Southern Ontario to central Maine. This boundary we shall call the "Pacific front" rather than the "Polar front" because there is undoubtedly a front between the "return Polar" air in the southeast and the true maritime Tropical air to the south, beyond the data coverage on which the chart was based.

The western edge of the "return Polar" air meets air from the southwest, Pacific air which has skirted the southern end of the main mass of the Rockies, in west Texas. This "front" or confluence is recognized by the synoptician,

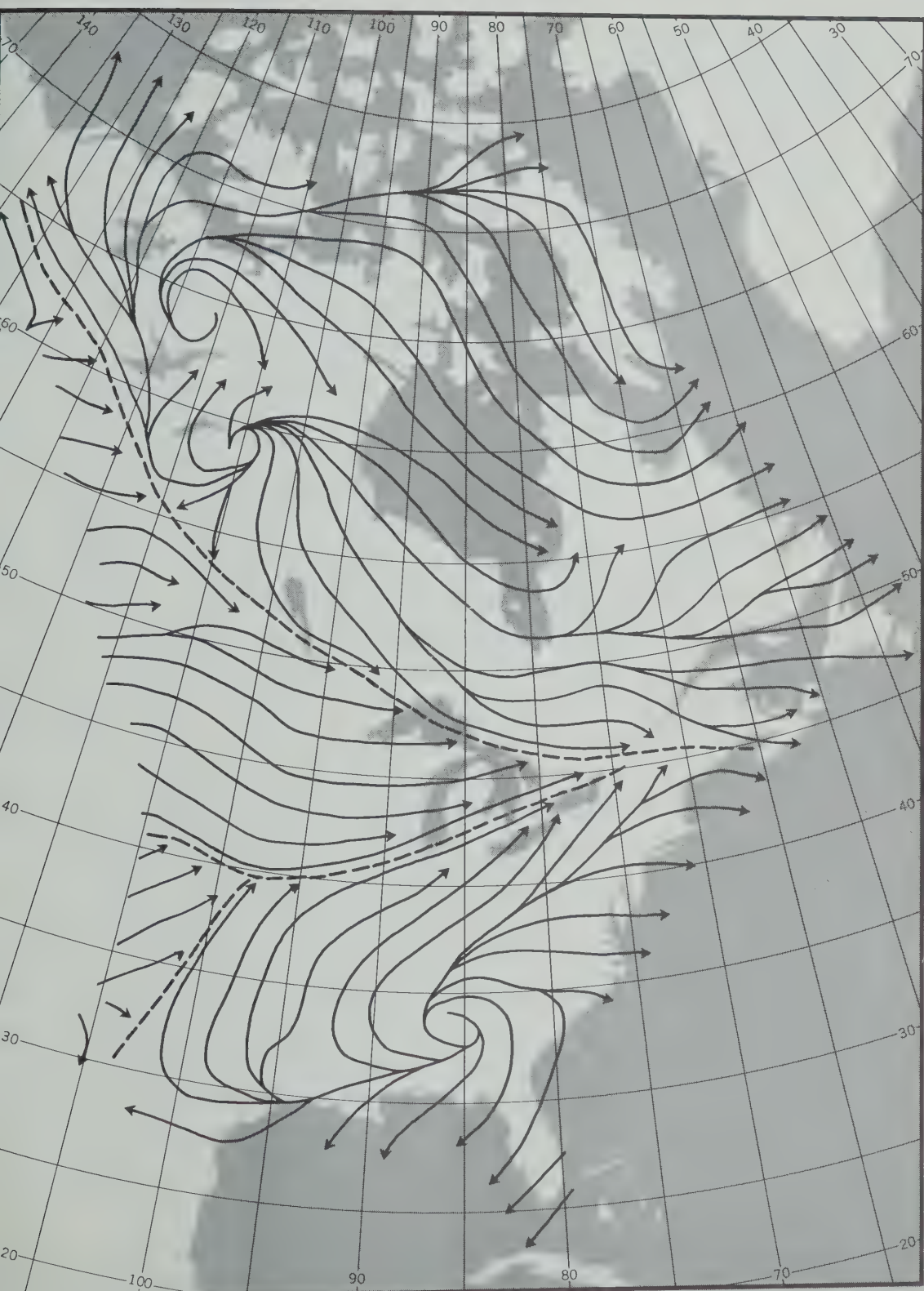


Figure 20. Streamlines of the surface resultant wind in November.

who frequently refers to it as the "West Texas front." For lack of a better name we shall retain that terminology.

In Canada, we see evidence of two airstreams, both cold--Arctic air, and true continental Polar air in a Canadian Anticyclone. This cold air converges with the fresh Pacific airstream along a broad, sweeping line from the Yukon, through central Saskatchewan, to the Great Lakes region and central Maine. At the risk of some ambiguity we shall call this the Arctic front, lumping for the moment both continental Polar and Arctic air as sufficiently similar for our present purpose.

Turning now to the independent data for December (Figure 21), independently analyzed, we find the same confluences and climatic-synoptic elements. Return Polar air from an anticyclone over the Gulf states meets "southwestern" air along a "West Texas" front now in east Texas, but the Pacific front still lies along a line from Fort Collins, Colorado to northern Missouri, southern Ontario and central Maine. A Canadian Anticyclone with continental Polar air and an Arctic airstream are both present, and the Arctic front lies in the same position it occupied in November.

In January, the "West Texas" front once again lies in west Texas, but the Pacific front occupies the same position it had in November and December (Figure 22), as does the Arctic front. The mean anticyclone over the Gulf Coast states is elongated as though the main position were over Georgia but with an alternate position in south-east Texas. In February these two centers are clearly defined (Figure 23) but the position of the "West Texas" front is unchanged and the Pacific front is in the same position as in November, December, and January. The main change is in the north, where though the Arctic front still lies in its earlier position in the west, its position in the Great Lakes area is shifted from northern Michigan to southern Michigan.

The streamline chart for March (Figure 24) shows the same "frontal" or confluence positions as does that for February. The major difference is found in the disappearance

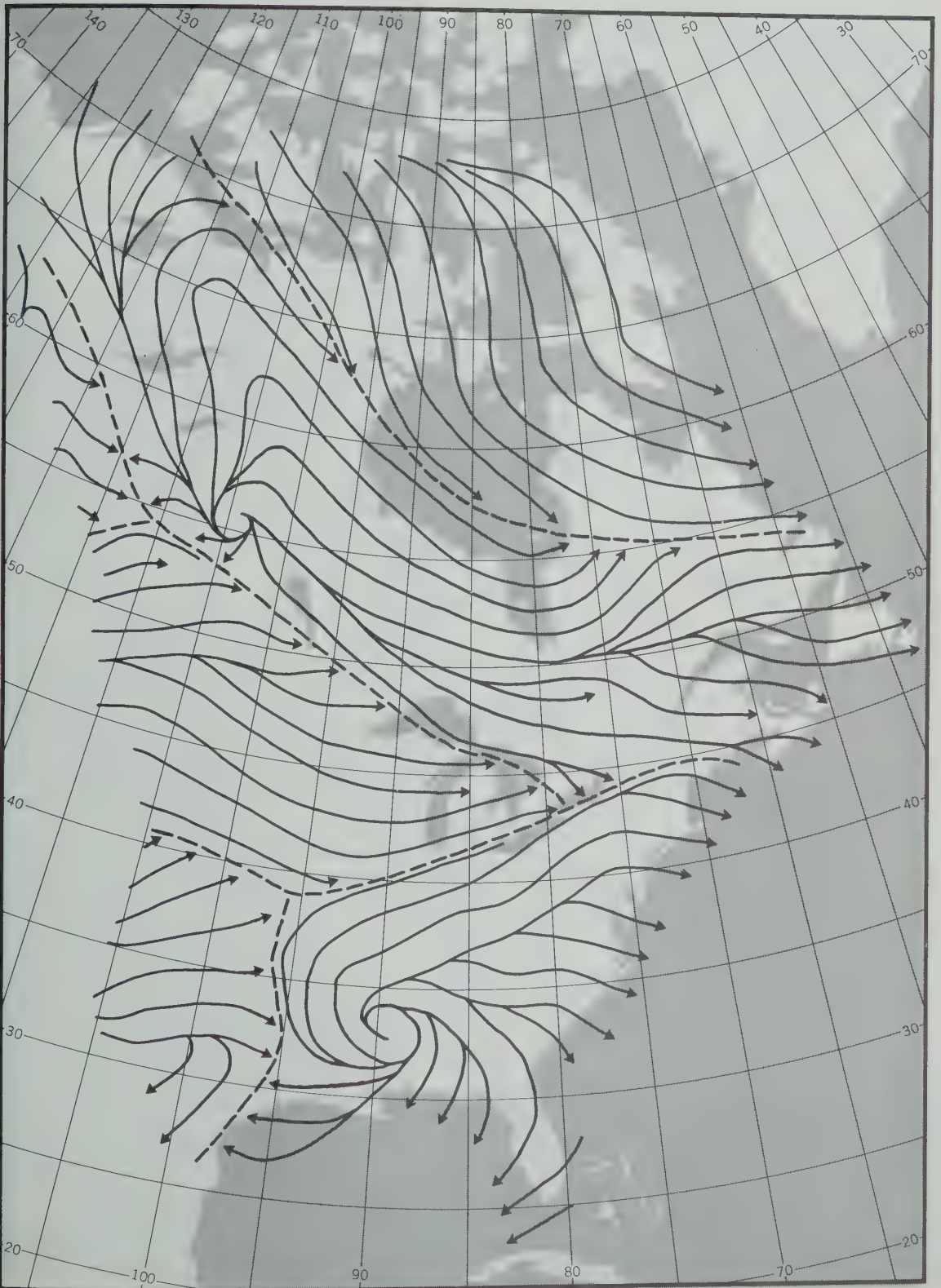


Figure 21. Streamlines of the surface resultant wind in December.

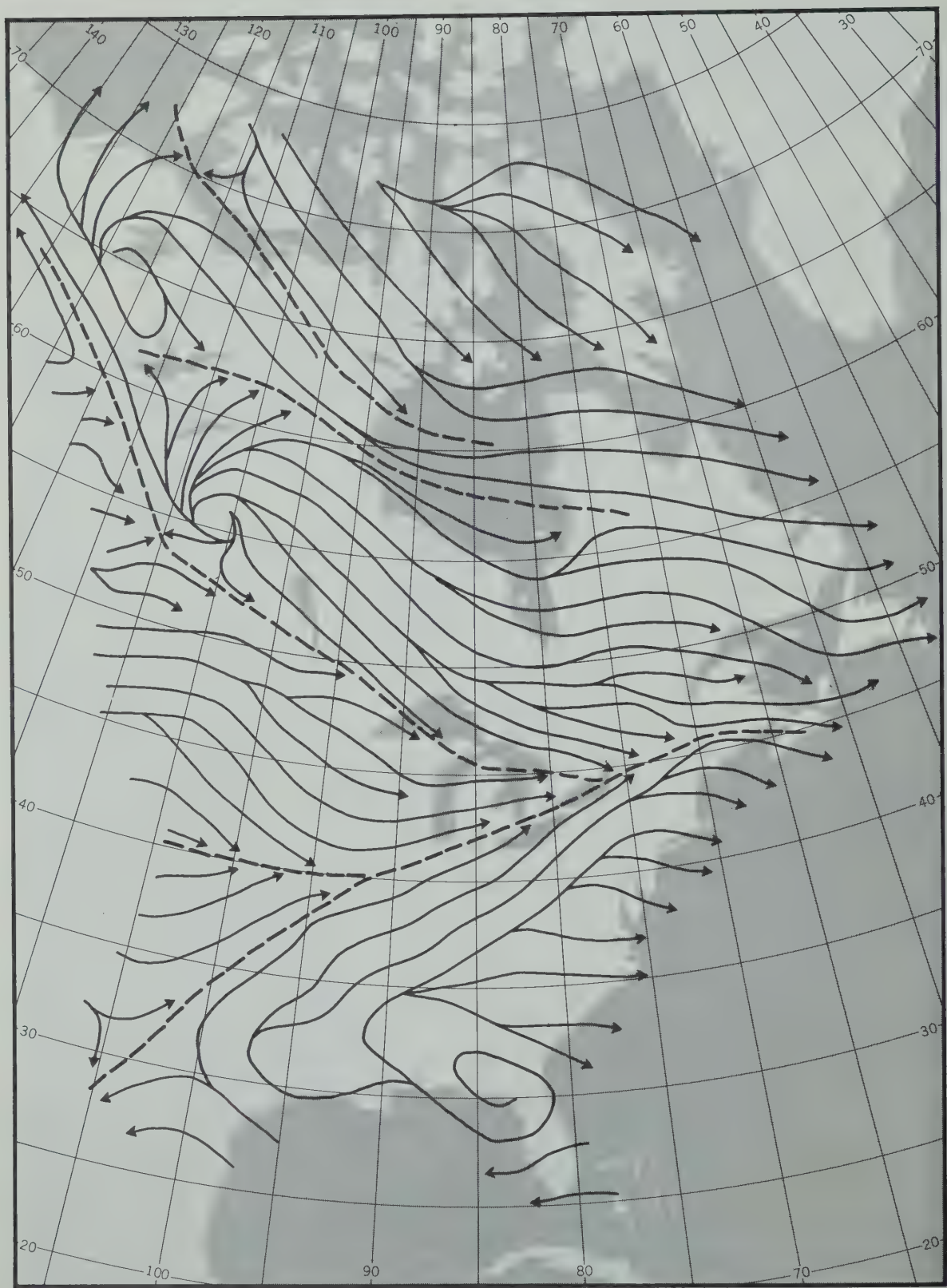


Figure 22. Streamlines of the surface resultant wind in January.

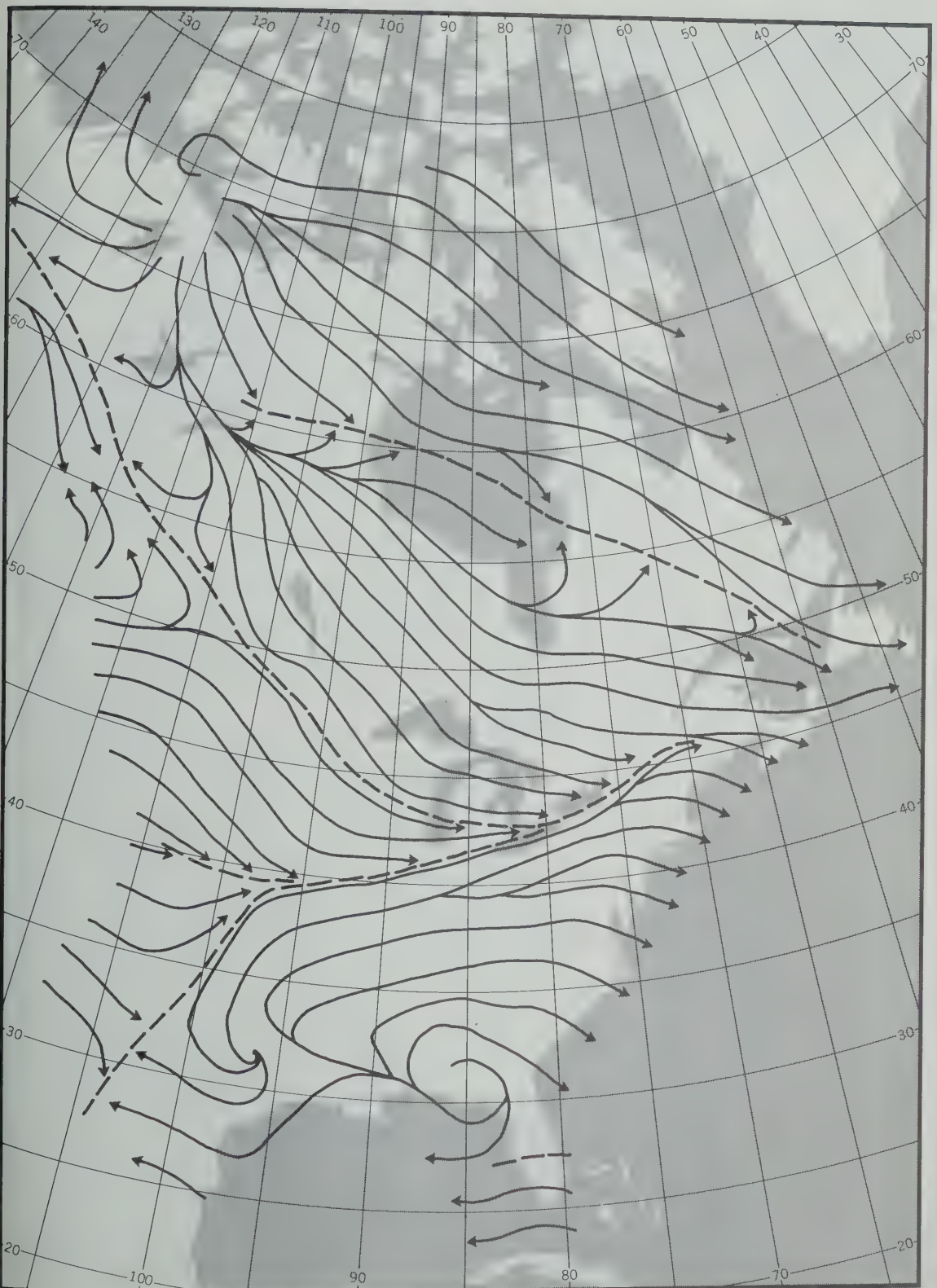


Figure 23. Streamlines of the surface resultant wind in February.

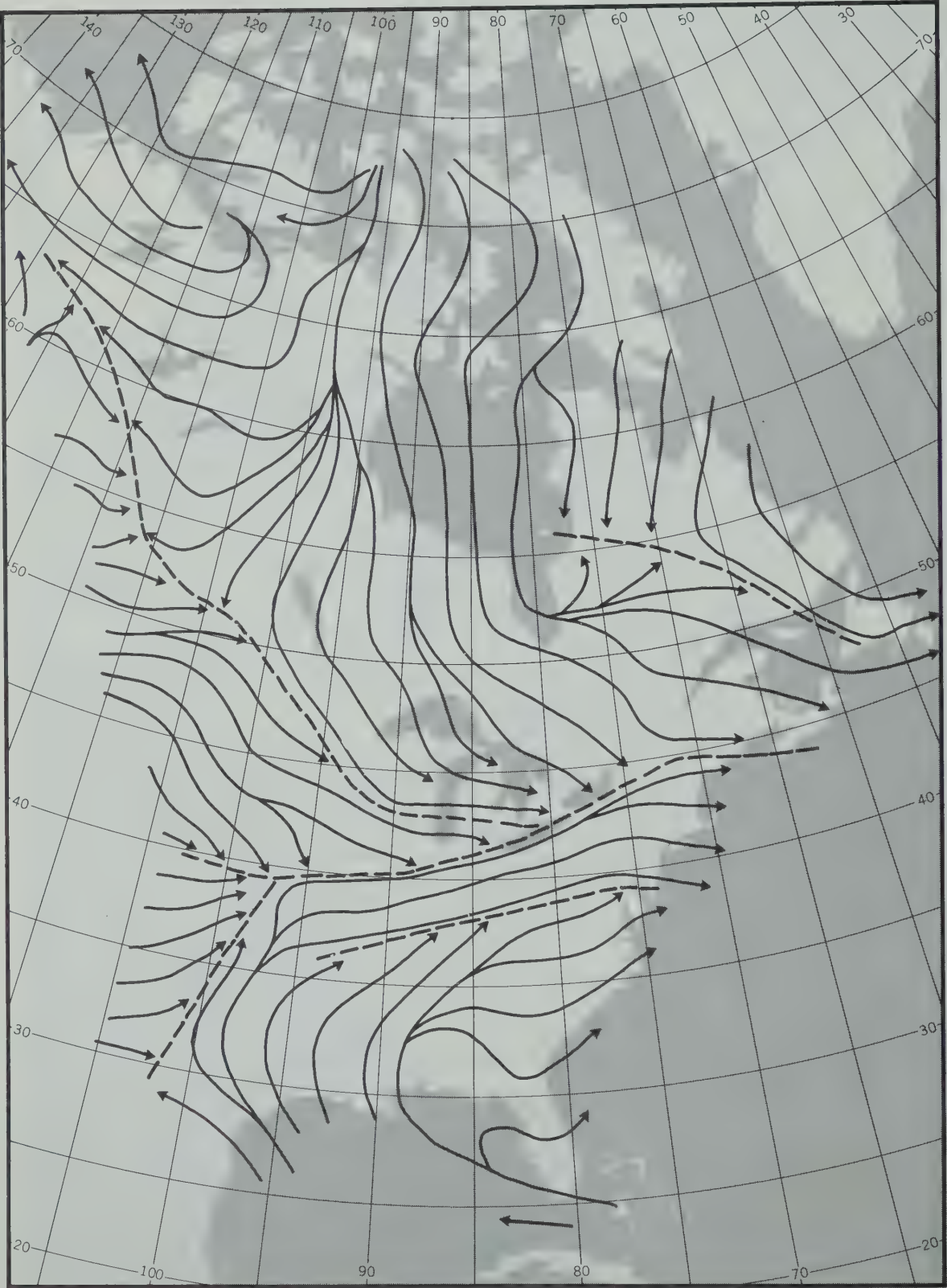


Figure 24. Streamlines of the surface resultant wind in March.

of evidence for a continental Polar airstream and anticyclone distinct from the Arctic airstream, the latter sweeping directly into the Great Lakes area. The anticyclone in the south also shows some changes, apparently representing the transition from a "return Polar" anticyclone to a sub-tropical anticyclone of maritime Tropical air, agreeing with the rapid March increase in frequency of thunderstorms in the central United States. Another point of change worth noting is the appearance during March of a secondary confluence paralleling the Pacific front but lying through northern Arkansas, Kentucky and Maryland. This may be associated with the late winter rainfall maximum just south of that line (Horn and Bryson, 1960).

Reviewing the charts in Figures 20-24, one finds very little change from month to month except for some oscillation of the "west Texas" front and the February-March dip of the Arctic front from the northern Great Lakes region to the southern Great Lakes. April and May (Figures 25 and 26) have streamline patterns very similar to each other which, however, are quite different than those which prevail from November through March. The wedge of fresh Pacific air which crosses the plains to a maximum eastern extent in northern Illinois in late winter (February-March) is pinched out in April and May between a southward expansion of the Arctic airstream and a northward expansion of the Tropical airstream. These two airstreams of maximum contrast meet along the line that was occupied all winter by the Pacific front, except in the midwest, where the Arctic-Tropical mean convergence bulges northward into southern Minnesota. It is not surprising, on examination of these charts, that the midwest has violent weather in April and May. Nor is it surprising that this is a season of fine weather (though still very cold) in the central Canadian sub-arctic, for the continental Polar-Arctic confluence of winter is gone and a broad diffluent stream of Arctic air prevails.

June (Figure 27) differs from May primarily in that the Tropical airstream bulges into the Dakotas, to Winnipeg

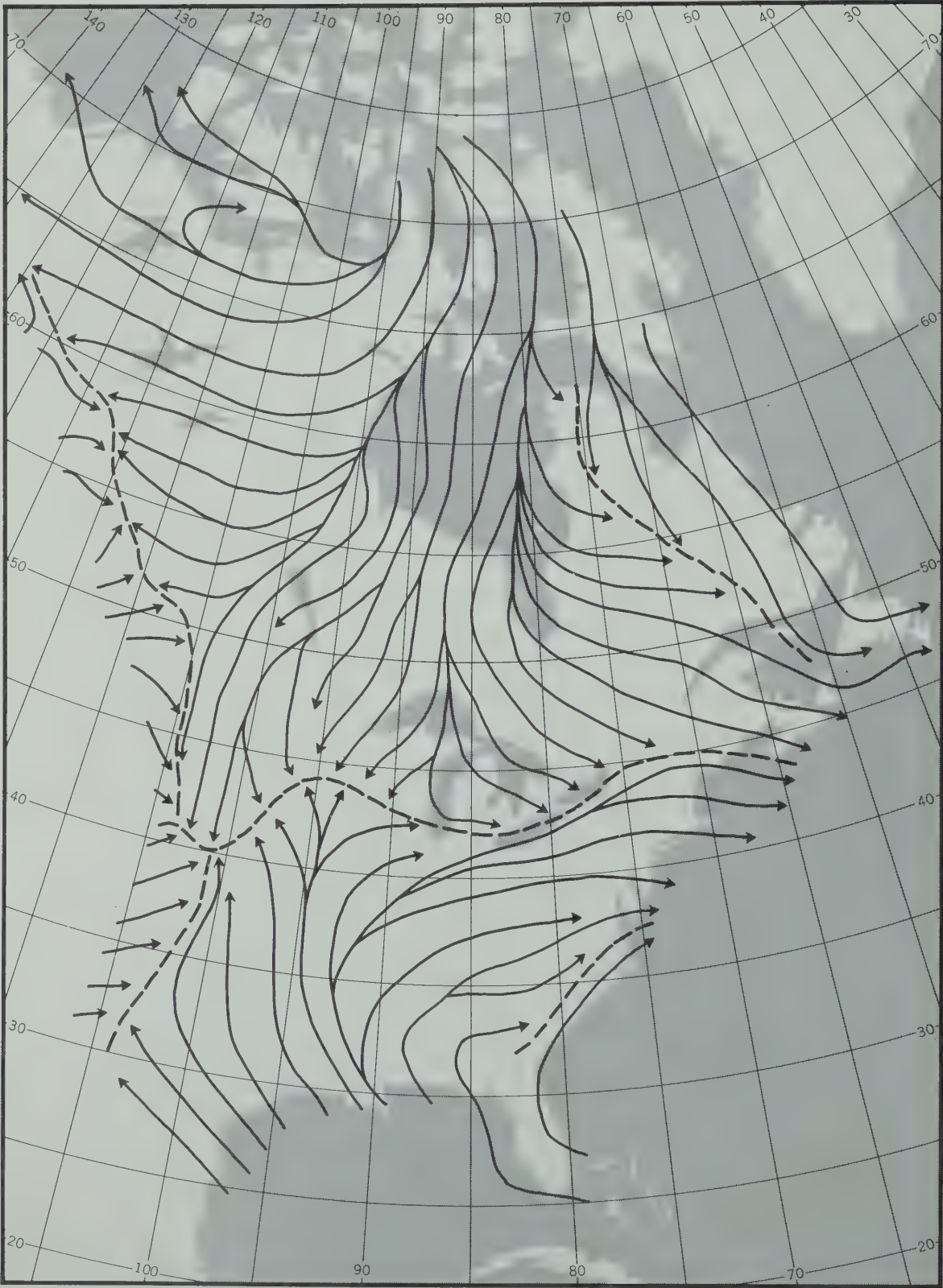


Figure 25. Streamlines of the surface resultant wind in April.

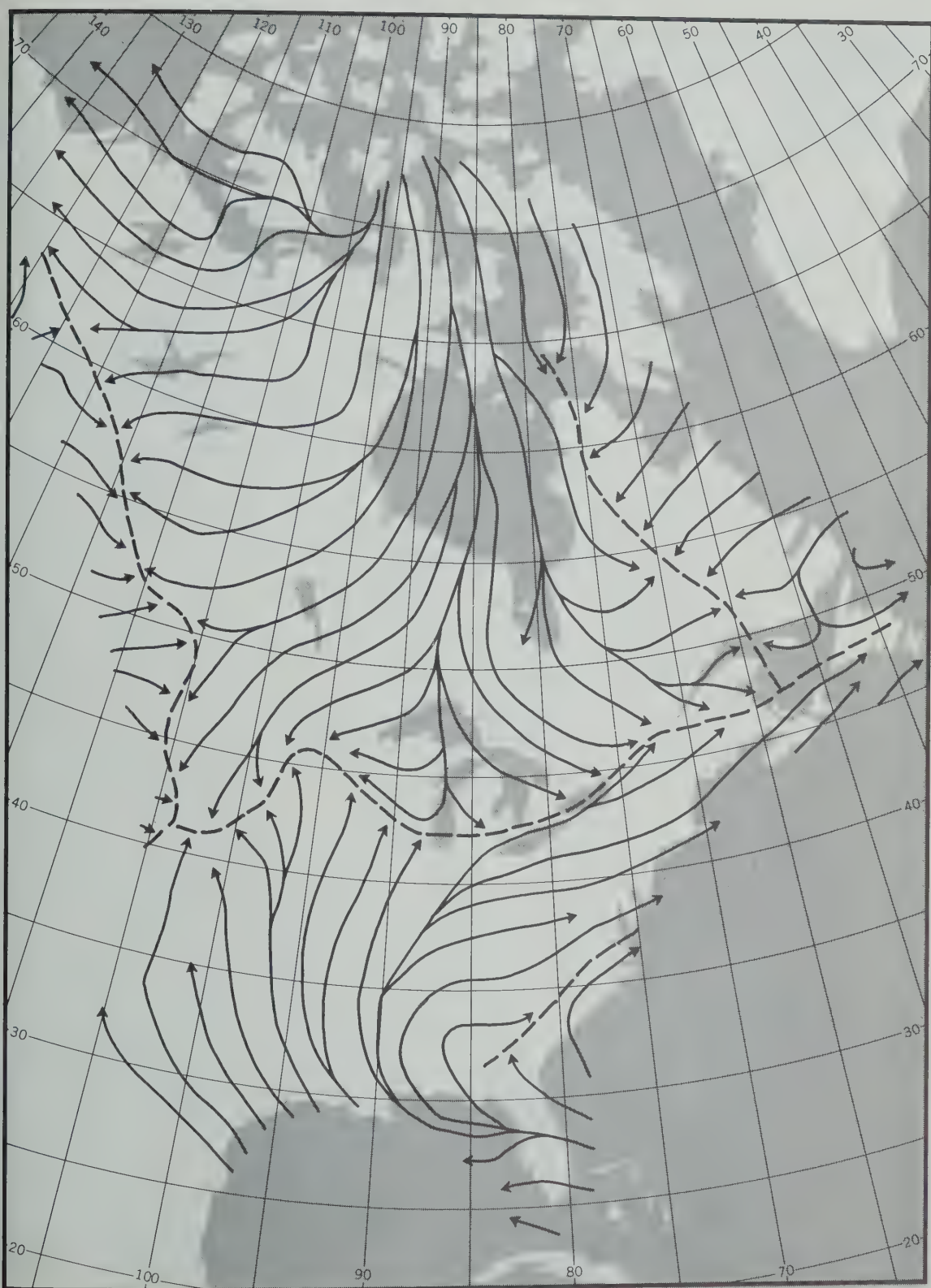


Figure 26. Streamlines of the surface resultant wind in May.

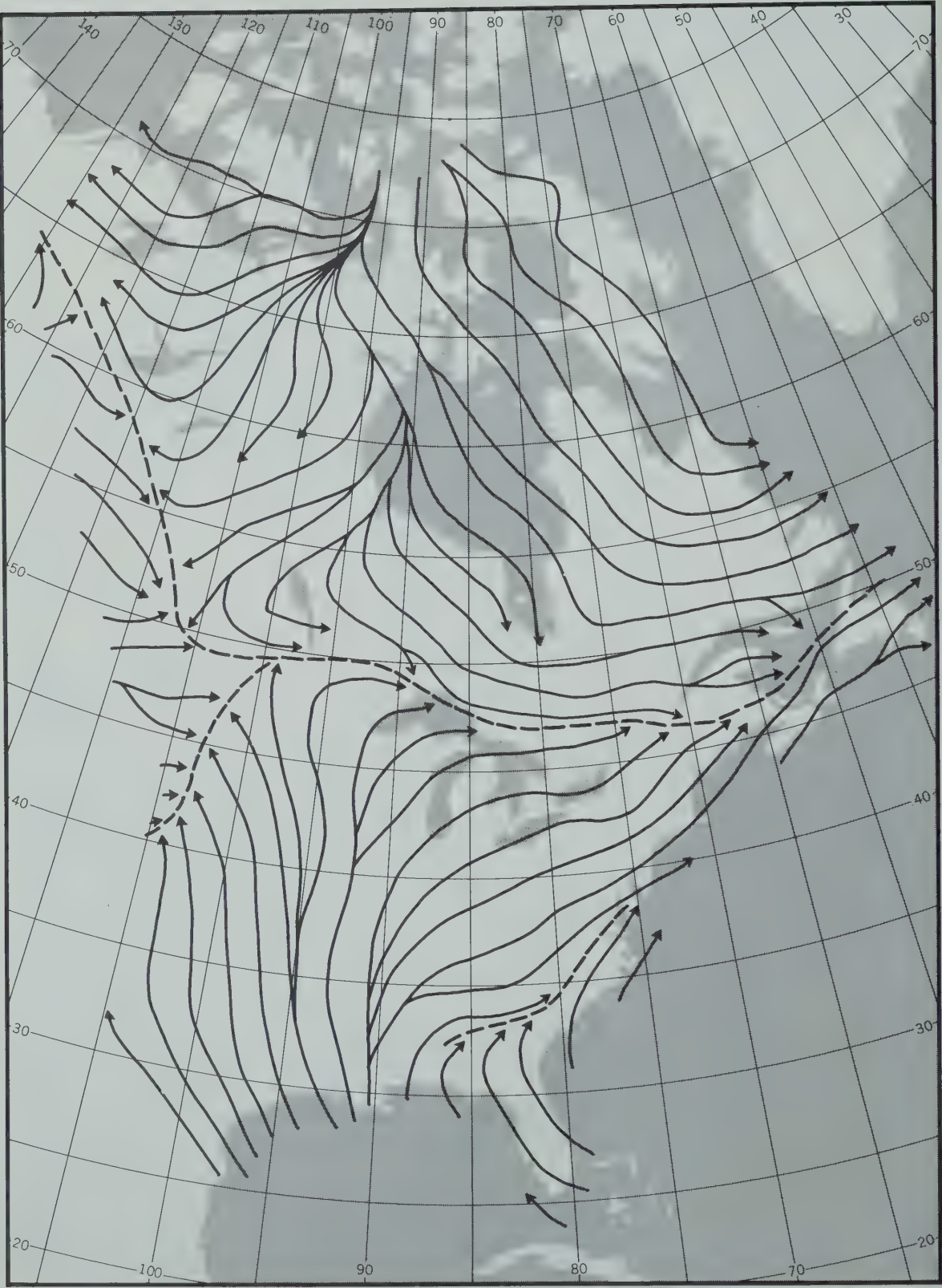


Figure 27. Streamlines of the surface resultant wind in June.

and over the Great Lakes. The confluence at the northern periphery of the Tropical airstream is still anchored near Fort Collins, Colorado and passes through Maine for the eighth consecutive mean month.

July and August (Figures 28 and 29) might as well be treated as a single unit, for the flow patterns are very similar indeed, yet quite different than April, May and June. The Tropical airstream reaches to the same limit in the Dakotas as it did in June, but now extends also into southern Quebec and Labrador.* The southern limit of Arctic air has retreated to a line which sweeps from east of Aklavik in Mackenzie Territory across Great Slave Lake to the southern end of Hudson Bay and northern Quebec. The data are quite far apart in this region, so that great precision cannot be attained in fixing the location of the mean southern edge of the Arctic air, but it clearly parallels and is near to the forest border. A wedge of Pacific air once again extends eastward south of the Arctic airstream. The boundary between the Tropical and Pacific airstreams is still anchored near Fort Collins, Colorado. Examining the charts for May, June and July, it would appear that June is a mixture of May and July patterns.

September (Figure 30) differs from August in three main respects: (1) the Arctic front appears to be a little farther to the south, (2) the Pacific airstream once again pushes across the Dakotas, and (3) the southeastern United States is once again dominated by an anticyclone. The boundary between the air spreading northward across the plains from this anticyclone and the fresh Pacific airstream is still

* One must remember, however, that this is the mean or resultant flow and other varieties of air clearly are quite frequent in this eastern region.

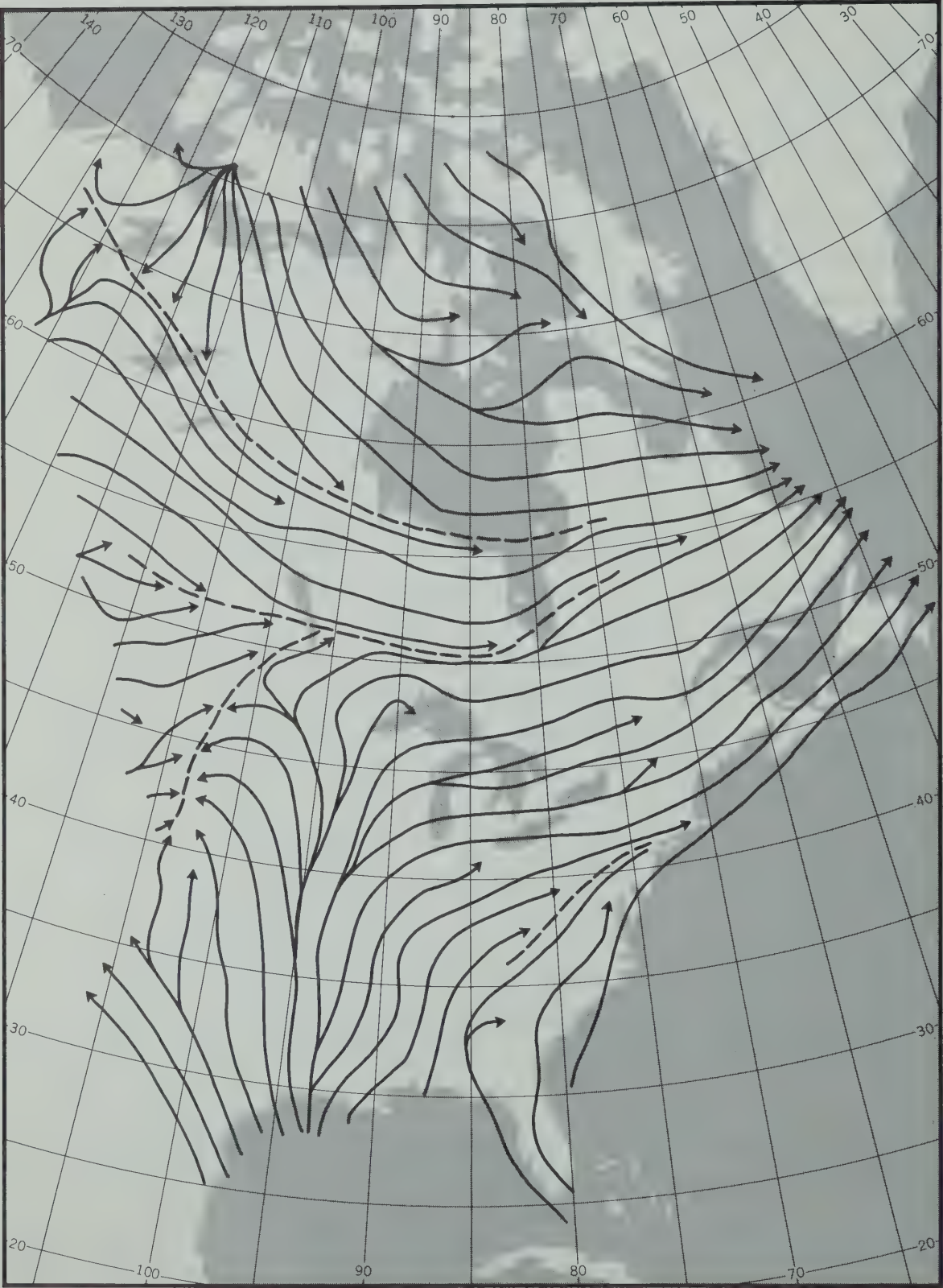


Figure 28. Streamlines of the surface resultant wind in July.

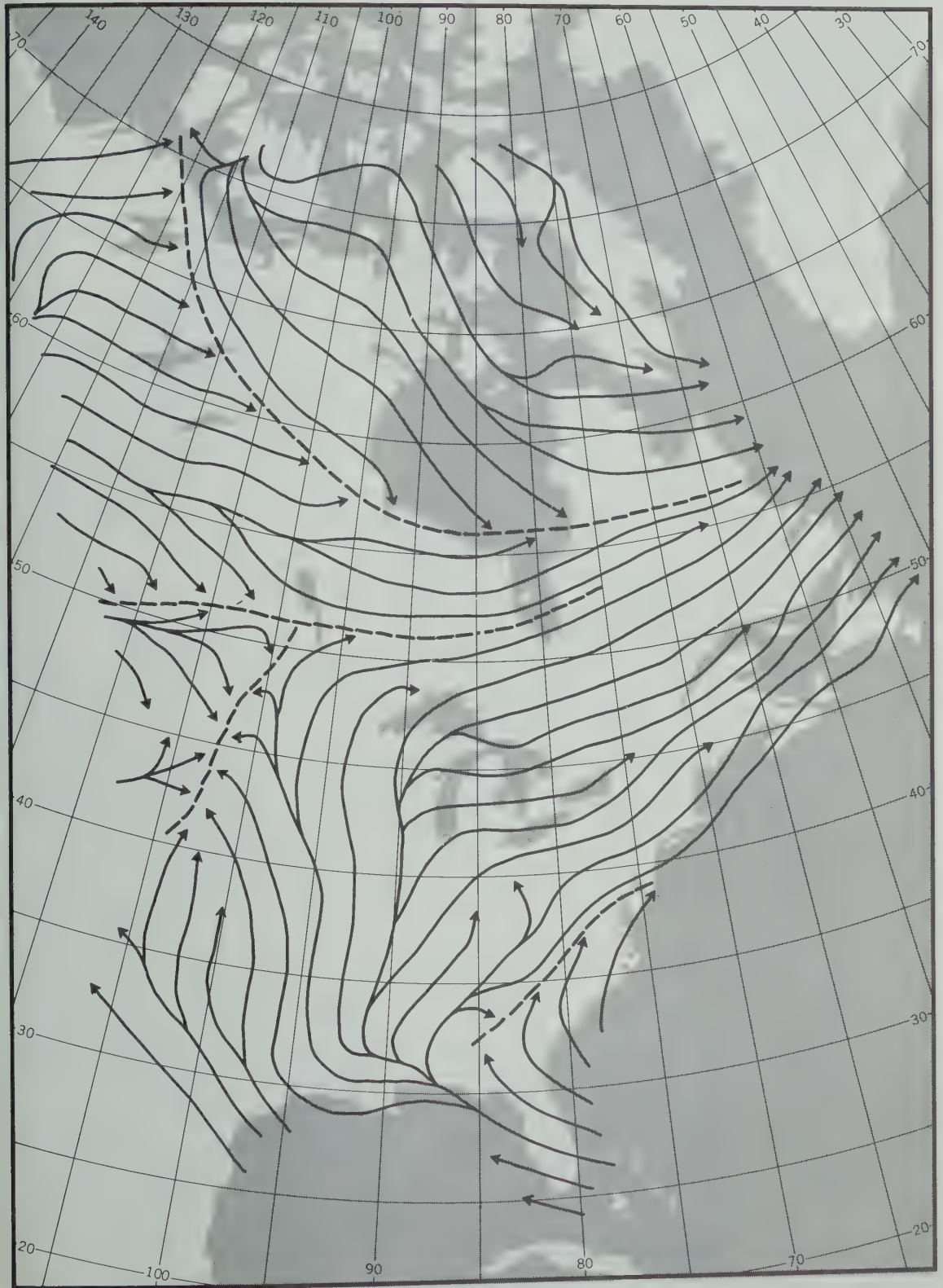


Figure 29. Streamlines of the surface resultant wind in August.

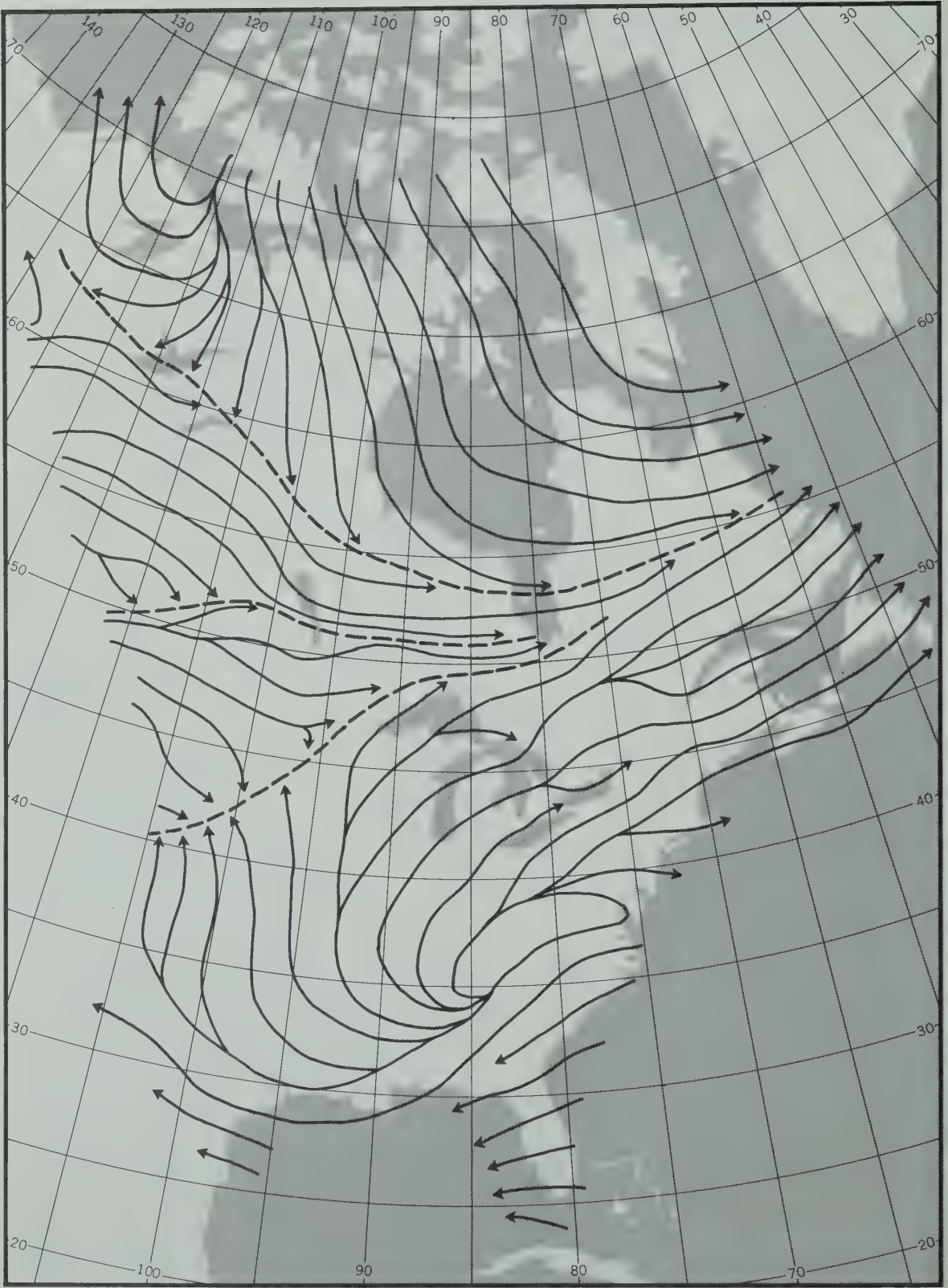


Figure 30. Streamlines of the surface resultant wind in September.

anchored in northern Colorado. October (Figure 31) is the only month where this is not true. In other respects the October pattern is very similar to that for September except for the southward withdrawal of the air from the southeastern anticyclone, its northern boundary being about the 46th parallel.

Then the winter pattern begins in November with the development and southward push of continental Polar air, the southward shift of the fresh Pacific airstream, and the reestablishment of the Pacific front in its winter position.

4.2 The Composite Airstream Pattern

In the preceding paragraphs the areas occupied by the various airstreams and the positions of the monthly mean confluences were discussed as they appear on the mean stream-line charts. Hypothetically one could superimpose the charts to obtain isochrones of the north-south annual march of the mean confluences or "fronts." In practice this breaks down for the "fronts" do not progress regularly north and south, but stay in one position for several months (a meteorological season) then move abruptly to a new seasonal position. This is very clearly shown on a chart containing all the monthly airstream boundaries (Figure 32). Distinct seasonal boundaries are quite localized in position. The areas, bounded and delineated by these mean "frontal" positions are characterized by a definite sequence of seasons each with its particular dominating airstream. These are natural or genetic climatic regions, defined entirely by meteorological parameters.

Consider as an example, the region occupied by fresh Pacific air in winter (Nov.-Mar.), maritime Tropical air in summer, and with an early spring burst of tropical air in April and May. There is only one such area on Figure 32, the diamond shaped area with apices near North Platte, Nebr., Redwood Falls, Minn., South Bend, Indiana, and north of Springfield, Mo. This distinctive climatic region, derived from the airstream patterns and sequences coincides with the

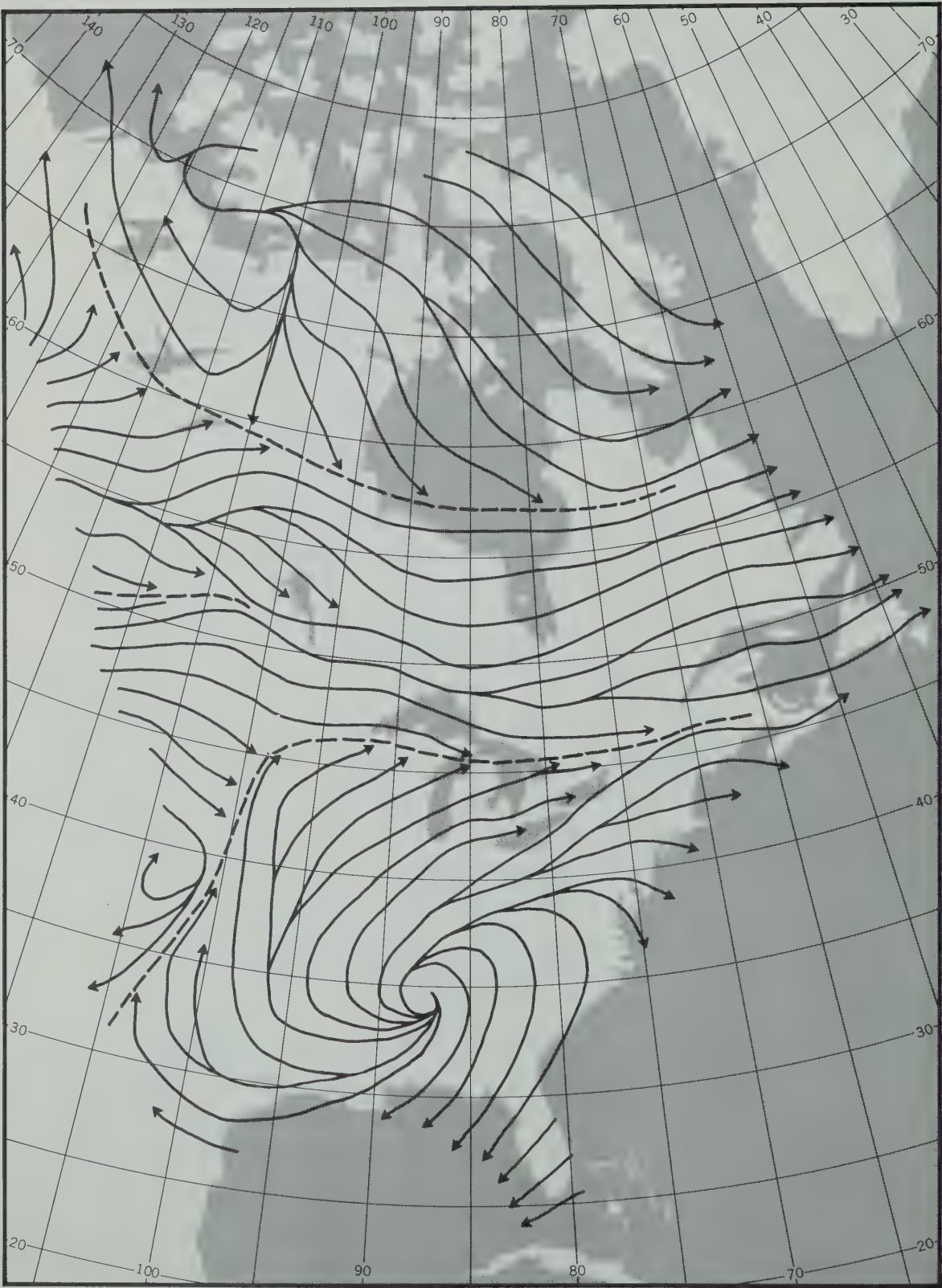


Figure 31. Streamlines of the surface resultant wind in October.

"corn belt" as defined by land use! There is, then, a distinctive "cornbelt" climate (Figure 33).

If one looks at the region occupied by the continental Polar and Arctic airstreams all winter and spring (Nov.-May) but by Pacific and Tropical air in summer (Figure 33) one finds a region stretching from the Rockies to the Atlantic which quite closely matches the distribution of boreal forest. The boreal forest climate is thus defined, and the forest itself lies between the summer and winter positions of the Arctic front. An exception is to be found at the base of the Canadian Rockies where the increased elevation produces a southward extension of the forest beyond the winter position of the Arctic front, but such topographically produced anomalies are to be expected.

Examination of the regions defined by the seasonal variation of airstreams and "fronts" reveals other definable climates for specific biotic regions; e.g. the tundra climate, characterized by year-around Arctic air dominance. Since the climatic regions defined by airstream and airmass are derived from climatic data independent of the biological data, yet correlate closely with the biotic regions, it would appear that there is at least quasi-equilibrium between the climatic pattern and the biotic pattern. Post-glacial shifts in the major biotic regions should then be associated with and indicative of shifts in the climatic pattern. This has, of course, been assumed for many years, but using climatic regions of the Koeppen type which are derived from the biotic regions, and not independently derived, one is suspicious of circular reasoning in suggesting a causal relation.

Assuming that such boundaries as the northern border of the boreal forest are closely and causally related to the summer position of the Arctic front (Figure 33), one would then deduce that the range of positions occupied by the modal location of that front in post-glacial time is given by the range of positions of the forest border. It has been shown by Bryson, Irving, and Larsen (1965) that this range has been on the order of 150 miles in the past 4000 years in Keewatin.

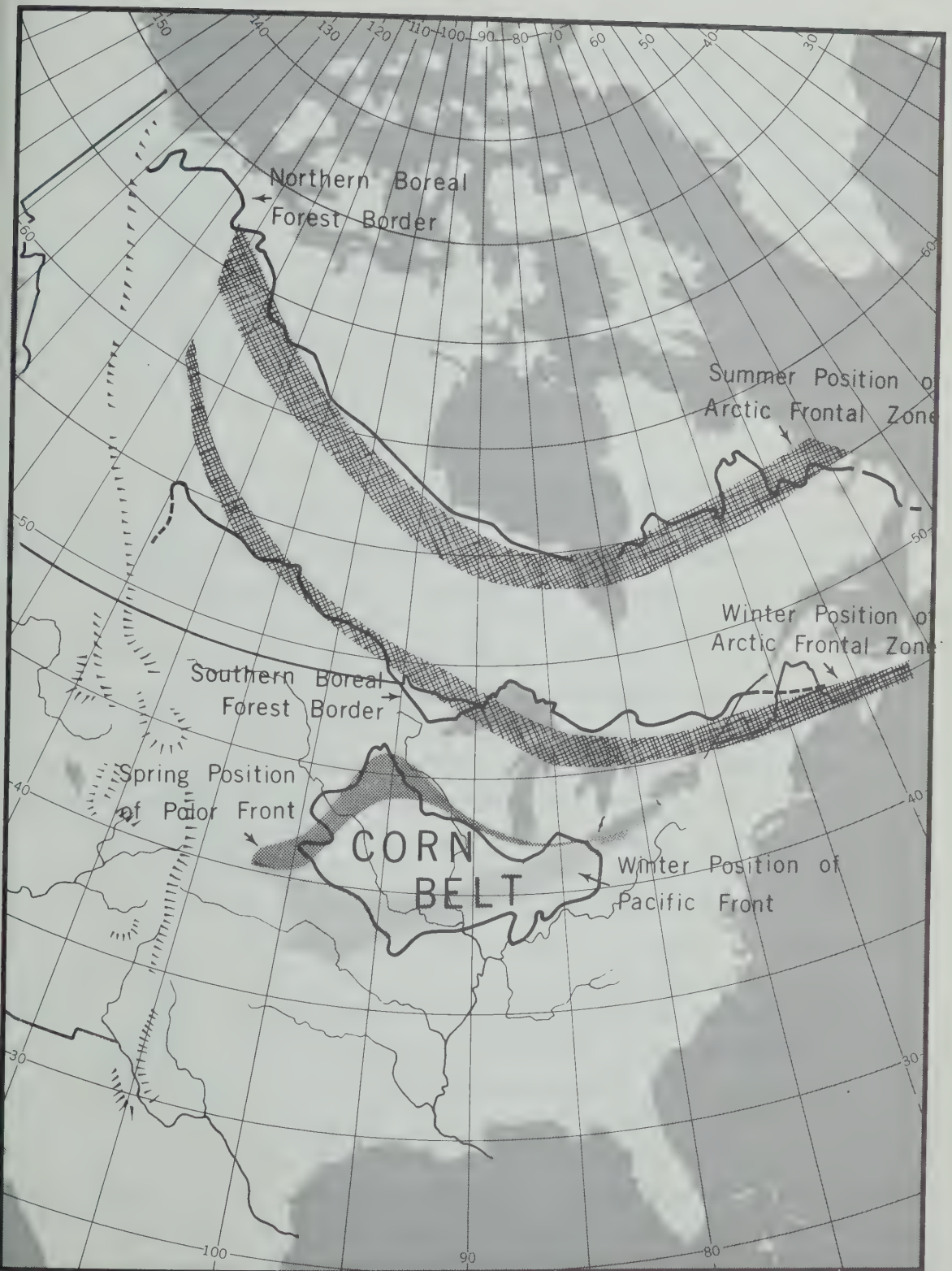


Figure 33. The coincidence of the "corn belt" and "boreal forest" biotic regions with meteorologically defined climatic (air mass) regions. Climatic regions are taken from figure 32, the "corn belt" from "Soils of the North Central Region of the United States" (1960), and the boreal forest generalized somewhat from Rowe (1959) and Larsen (1965).

5. SUMMARY AND DISCUSSION

In the preceding chapters data have been presented on the summer airmass frequencies over central North America, and especially Canada, which show that similar patterns can be derived both from trajectory analysis and temperature analysis. It was pointed out in the chapters where these data were discussed that if one delineates the regions wherein a given airmass dominates, i.e. is present more than half of the time, the zone of transition from Arctic air dominance to Pacific air dominance seems to coincide quite closely with the forest border zone at the northern edge of the Boreal Forest.

In chapter four, surface resultant streamline analyses for each month of the year were presented. Particularly close coincidence was found in summer for the confluence (mean front) between Arctic and Pacific airstreams and the zone of transition between Arctic and Pacific airmass dominance. This is taken as confirming the initial hypothesis that the northern edge of the Boreal Forest or the southern edge of the Tundra is associated with the mean position or modal position of the Arctic front in summer.

There are other striking relationships brought out by the charts of airmass frequencies for July and streamlines for the various months. Of particular note is the parallelism of the winter patterns of the airstreams in the Great Plains and the summer airmass regions (Figures 19 and 32). The transition zones between cT air, mT air, and Pacific air form a Y-shaped pattern centered near Dodge City, Kansas with branches towards Denver, the Big Bend region of Texas, and St. Louis. This same pattern appears on the frontal or confluence zones between the winter equivalents of these three airmasses. Evidently "outbreaks" of southwestern and Pacific air in summer follow the same general pattern that they follow in winter. That they should is not very surprising in light of the abundant evidence on the charts showing the profound effect of topography on the airmass and

airstream patterns.

One indication of the topographic control of the patterns may be seen by comparing the streamline chart for July (Figure 28) with the composite airmass chart (Figure 19). The streamlines at the base of the Rockies exhibit different patterns spreading from specific locations along the mountain front. These same regions can be identified as the core regions of maximum frequency of the various varieties of Pacific air discussed in chapter 3. The core region of the Yukon variety of Pacific air (Y) is found in the diffluent region near $60-61^{\circ}\text{N}$, Canadian Rockies air (CR) is most frequent in the diffluent region of southern Alberta, and the airmass labelled NR for the northern U. S. Rockies is most frequent in the diffluent region of eastern Wyoming. That the northern and southern of these three regions represent gaps in the cordillera through which the winds sweep Pacific air into the continental interior is quite apparent. Why there should be a maximum intrusion of Pacific air with distinctive character into central Alberta is less apparent, though there seems to be little question of its reality. Perhaps it is due to the maximum trans-montane pressure gradient in this region coupled with the lower elevations of the Coast Mountains in southern British Columbia.

Another indication of topographic control is to be found on the streamline charts of Figures 20 through 31. The Arctic front seems to be topographically anchored at the northern end of the Cordillera near Aklavik year-round, but swings north and south with the seasons in the continental interior where the terrain is relatively flat. Similarly the confluence called the Pacific front in chapter 4 is anchored at the northern end of the southern Rockies for eleven months of the year and swings north and south with the seasons in the plains area. On the east coast the position of the "Pacific front" is far less variable with the seasons than in the interior, and the location suggests that oceanographic

conditions might be an important factor in that region.

Still a third example is to be found in the position of the "chinook front" between Pacific and Arctic air in spring. From the Yukon to Montana this boundary approximates the 2500 ft contour, suggesting a mean depth of the western edge of the Arctic airmass over which the Chinook air descending the high plains finally spreads (Figures 25-26).

Clearly, there is a need for extending the airmass analyses presented here to months other than July before the interpretations presented in this paper can be regarded as more than advanced working hypotheses. Also more detailed attention must be paid to the montane area, and to the southeast, especially in winter. These extensions, however, must await first the acquisition of better wind data for the southeast; second, the application of the objective computer method for reducing frequency distributions to partial collectives; and third, the development of a technique for examining the climates of the montane area. Enough progress has been made on the second of these requirements to know that the graphically obtained solutions are not much different than those obtained by least squares fitting of a series of normal distributions to the total frequency distribution. It would appear, however, that a genetic regionalization of climates, using synoptic climatology of the sort presented here, is possible.

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APPENDIX: NON-LINEAR PARAMETER ESTIMATION FOR THE PARTIAL COLLECTIVE MODEL OF AIR MASS ANALYSIS

BY Donald R. Johnson

Introduction

In this appendix, a technique of air mass analysis by the partial collective method (Essenwanger, 1954) utilizing least squares estimation is briefly presented. In the air mass analysis by the partial collective method, the assumed mathematical model to represent the multimodal distribution of daily maximum temperatures is a family of normal distributions, hereafter called the partial collective model. The parameters of the partial collective model, the mean temperature, the variance, and the percentage frequency of occurrence for each normal distribution enter non-linearly in the mathematical model. Thus, the parameter estimates must be determined by non-linear least squares estimation. The object of this development of numerical methods to estimate the partial collective parameters is to facilitate future climatic studies of air mass frequency distribution, produce information concerning the precision of the parameter estimates and to investigate the adequacy of the partial collective model.

The Partial Collective Model

In the basic paper (Bryson, 1966), the partial collective model is used to describe the monthly probability histogram of the daily maximum temperatures occurring at a climatological observing station. Two "a priori" factors suggest that the family of normal distributions is the natural model to represent the maximum temperature histogram. The first factor, noted by Essenwanger (1954), is the multimodal nature of the probability histogram. From air mass

theory, one associates the coldest daily maximum temperature with a particular air mass, likewise milder maximum temperatures with other air masses, until the hierarchy of air masses is complete. In the probability histogram, the individual modes can be associated with the different characteristic air mass temperatures and the frequency of air mass occurrence at the observing station. The second factor, although possibly more subtle, indicates that the normal distribution is the proper function to represent the distribution of maximum temperatures for each air mass. The spread of temperatures about one mode physically represents the temperature departures due to many air mass modification processes that occur along the different trajectories from the air mass source region to the observing station. Since many of the modification processes may be described as "independent effects" according to the Central Limit Theorem (Cramér 1946), the distribution of daily maximum temperature for an air mass about one characteristic temperature will tend to be the normal distribution.

In the analysis, separate probability histograms are formed for each month from the daily maximum temperature series extending for several years. The equal class intervals of the probability histogram are

$$(T_s - \delta/2) \leq T_s < (T_s + \delta/2); (s = 1, \dots, M) \quad (1)$$

where T_s is the mid-point temperature in whole degrees and δ is the size of the equal class intervals. T_1 and T_M are the lowest and highest mid-point temperatures whose class intervals contain the lowest and highest observed temperatures respectively. The ordinate height of each class interval for the probability histogram is

$$f_s = m_s / N \quad (2)$$

where n_s is the number of daily maximum temperatures occurring within the s -th class interval and N is the total number of observations. The lXM vector of observations, \underline{p} , contains the values of the ordinate heights of the M class intervals. The envelope of the probability histogram obtained by connecting the mid-point ordinate heights by a smooth curve represents the function to be estimated by the partial collective model.

The model consisting of the family of normal distributions is formed from the definition of the ordinate height of a normal distribution given by

$$p(y) = \frac{1}{\sqrt{2\pi}\sigma} \exp \left\{ -\frac{1}{2} \left(\frac{y - \eta}{\sigma} \right)^2 \right\} \quad (3)$$

where η , the mean, and σ , the standard deviation, are the parameters for the distribution of the variate y . Following this definition, the true ordinate height component of the t -th ($t = 1, \dots, k$) air mass for the s -th class interval is

$$y_{ts} = \frac{\chi_t}{\sqrt{2\pi}\sigma} \exp \left\{ -\frac{1}{2} \left(\frac{T_s - \eta_t}{\sigma_t} \right)^2 \right\} / Z \quad (4)$$

where η_t , the true mean temperature, σ_t , the true standard deviation, and χ_t , the true percentage frequency of occurrence, are the parameters for the t -th air mass. Z , the normalizing element given by summing over all air masses and all class intervals, is

$$Z = \sum_{s=1}^M \sum_{t=1}^k \frac{\chi_t}{\sqrt{2\pi}\sigma_t} \exp \left\{ -\frac{1}{2} \left(\frac{T_s - \eta_t}{\sigma_t} \right)^2 \right\} \quad (5)$$

The true total ordinate height representing all k air masses for the s -th class interval given by the summation of the k component heights is

$$y_s = \sum_{t=1}^k y_{ts} \quad (6)$$

$$y_a = \sum_{t=1}^k \frac{y_t}{\frac{1}{2\pi} \sigma_t} \exp \left\{ -\frac{1}{2} \left(\frac{T_a - n_t}{\sigma_t} \right)^2 \right\} / Z \quad (7)$$

Equation 7 is the partial collective model which is used to represent the observed histograms. One notes that the total number of parameters, $3k$, is three times the number of air masses which are present in the probability histogram. For convenience of notation, the partial model, equation 7, is expressed as

$$\underline{f} = g(\underline{T} | \underline{n}, \underline{\sigma}, \underline{\chi}) \quad (8)$$

where \underline{f} is the $MX1$ vector of true ordinate heights, \underline{n} , $\underline{\sigma}$ and $\underline{\chi}$ are the $kX1$ vectors of true air mass parameters and \underline{T} is the $MX1$ vector of mid-point temperatures.

The partial collective parameters enter non-linearly into the mathematical model. Hence, the usual method of linear estimation (of the parameters) by least squares does not apply and a non-linear estimation technique is utilized. The non-linear technique of least squares estimation is based on the sums of square function given by

$$S(\underline{n}, \underline{\sigma}, \underline{\chi}) = \sum_{a=1}^M (f_a - \underline{f}_a)^2 \quad (9)$$

$$= \sum_{a=1}^M (f_a - g(\underline{T} | \underline{n}, \underline{\sigma}, \underline{\chi}))^2 \quad (10)$$

The optimum parameter estimates $\hat{\underline{n}}$, $\hat{\underline{\sigma}}$ and $\hat{\underline{\chi}}$ of the true parameters are determined by selecting those values which makes S a minimum and are frequently referred to as least squares estimates. The minimization of S is accomplished by iteration and employs a subroutine from the Wisconsin Computing Center based on a method originally due to Gauss (1821) and applied by Meeter (1964).

Maximum Likelihood Properties of the Least Squares Estimates

Least square estimates by this technique are also maximum likelihood estimates (Fisher, 1922) and possess certain desirable properties (Mood, 1950) if the following three assumptions are satisfied:

The first, Assumption I, is that the errors, ϵ_i , defined by

$$\epsilon_i = f_i - \hat{f}_i$$

are independent of the errors ϵ_j for all $i \neq j$.

The second, Assumption II, is that the expected value of the errors is zero (there is no systematic bias in the errors, ϵ_i).

The third, Assumption III, is that the probability distribution of the errors is the normal distribution with variance, σ^2 . Hereafter, the assumptions are referred to by Roman Numeral.

In essence, Assumptions I and II require that any departures of the observation from the true value of the ordinate height be due entirely to random independent errors. Since the ordinate heights of the probability density functions are determined from daily values of temperatures, it is essential that the error components of the daily maximum temperature observations be random and independent, if these two assumptions are to be satisfied. Such is usually the case except for an observer's tendency to record even values in preference to odd values, or the temperature sensor may be biased. The former bias error may be eliminated by setting δ , the class interval, equal to two degrees. If the sensor bias error is present, the estimating procedure is valid except the least squares parameter estimate of each air mass mean temperature will be biased by the amount of the calibration error of the thermometer.

There are two factors which indicate that Assumption III is satisfied. The first is that the observational errors are nearly normally distributed if the bias error is non-existent

(Margenau, 1950). Furthermore, the observational error component of the ordinate height is a result of the sum of the nearly normally distributed temperature observational errors, thus the Central Limit Theorem dictates that error components of the ordinate heights are random and normally distributed (Cramér, 1946). In view of the valid physical evidence that the three assumptions are satisfied, the least square estimates of the partial collective parameters determined by the minimization of S possess the desirable properties of maximum likelihood estimates.

Results

The preliminary results of the least squares estimation of air mass parameters are very promising. Only one solution is presented; however, it is indicative of the successful estimation of ten cases. The initial input to the program requires an estimate of the number of air masses present in the histogram, the initial parameter estimates for the vectors of η , σ , and ψ as well as the daily maximum temperatures used to form the probability histograms. From the probability histogram, the ordinate height vector, \underline{f} , and the vector of mid-point temperatures, \underline{T} , are determined and used in the iteration subroutine to gain the maximum likelihood estimates of the air mass parameters $\hat{\eta}$, $\hat{\sigma}$ and $\hat{\psi}$.

Figure 1 for Pittsburgh, Pennsylvania presents the observed probability histogram and the results of the partial collective model estimates from the initial input parameter values. For this diagram Bryson's parameter estimates from his objective analysis are used as the initial parameter estimates of the partial collective model. The five normal distributions representing five air masses and the total envelope of the sum of the normal distribution ordinate heights are represented by the smooth curves in the lower half of the figure. The residual histogram is displayed in the upper half of the figure and is given by the differences

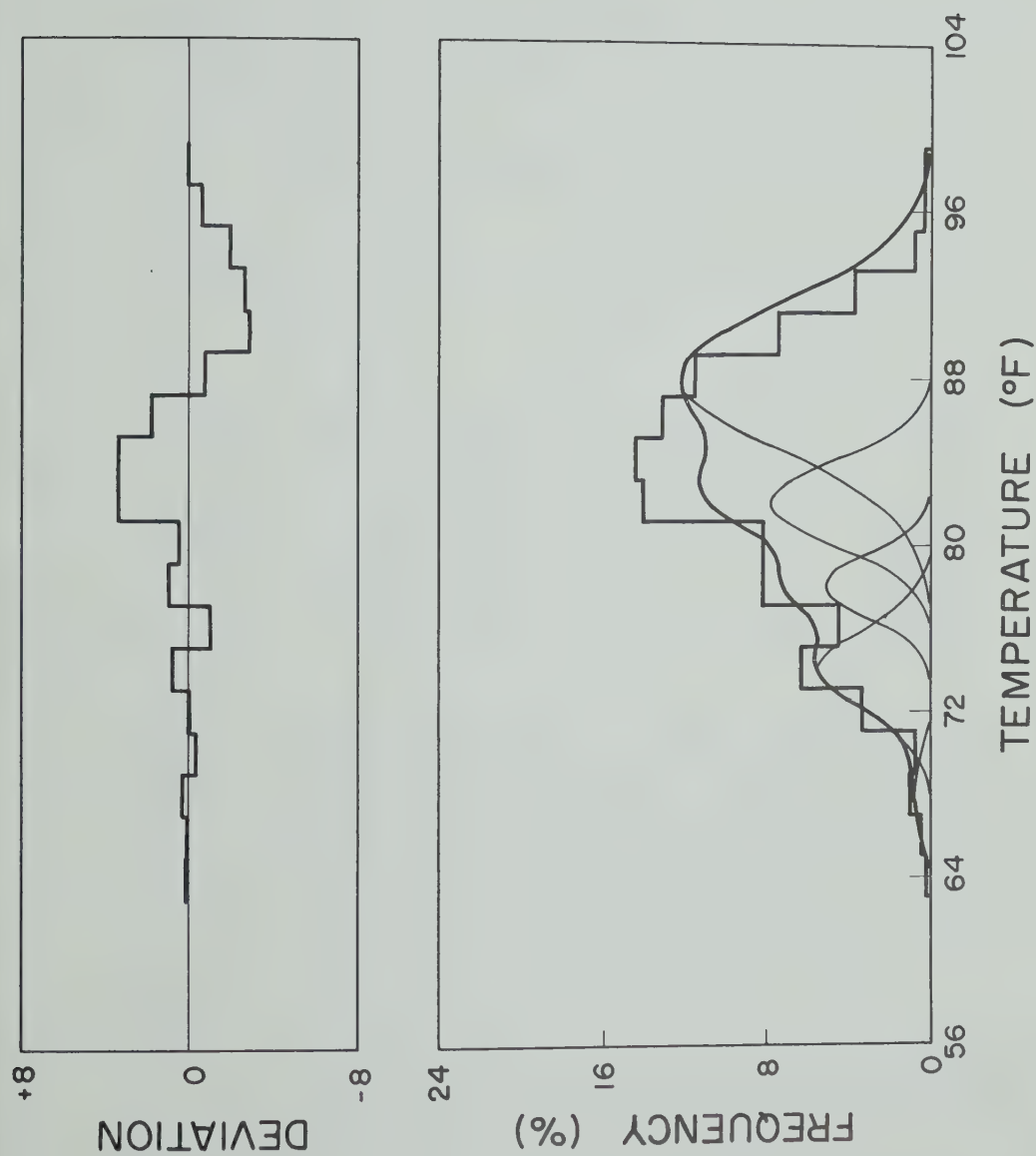


Figure 1. Observed probability histogram and the results of the partial collective model graphical estimates for Pittsburgh, Pa.

of the ordinate heights of the observed histogram and the initial ordinate heights of the partial collective model. In this figure the area lying under both the observed histogram and the normal distribution envelope is unity. Thus, the area lying under the normal distribution for each air mass represents the initially estimated percentage frequency of occurrence for each air mass. All of the initial parameter estimates are presented in Table I.

Table I: Air Mass Parameter Estimates for Pittsburgh, Pennsylvania

| | \hat{n}_t | | $\hat{\sigma}_t$ | | $\hat{\chi}_t$ | |
|-----|-------------|-------|------------------|-------|----------------|-------|
| | Initial | Final | Initial | Final | Initial | Final |
| I | 68.0 | 67.8 | 2.0 | 1.88 | 2.0 | 2.42 |
| II | 74.0 | 73.7 | 2.0 | 1.53 | 14.0 | 12.39 |
| III | 78.0 | 77.7 | 1.5 | 1.18 | 10.0 | 9.97 |
| IV | 82.0 | 82.0 | 2.0 | 1.94 | 20.0 | 24.00 |
| V | 88.0 | 86.8 | 3.5 | 3.31 | 54.0 | 51.23 |

In a comparison of the tabular values and Figure 1, it is clear that temperature estimates can be uniquely associated with the individual air mass curves. The residuals show that the mean temperature estimate of the warmest air mass is slightly high. It is important to check the initial residual vector to determine the accuracy of the initial guesses, since the number of iterations necessary to attain the optimum estimates is largely determined by their magnitude. Furthermore, since the partial collective model is non-linear in the parameters, it is possible to determine a local minimum for the sums of squares function with physically unrealistic values for the air mass parameter estimates. This possibility is enhanced by poor initial estimates for the air mass parameters or by trying to determine a larger number of air masses than are present on the histogram.

Figure 2 for Pittsburgh presents the excellent results

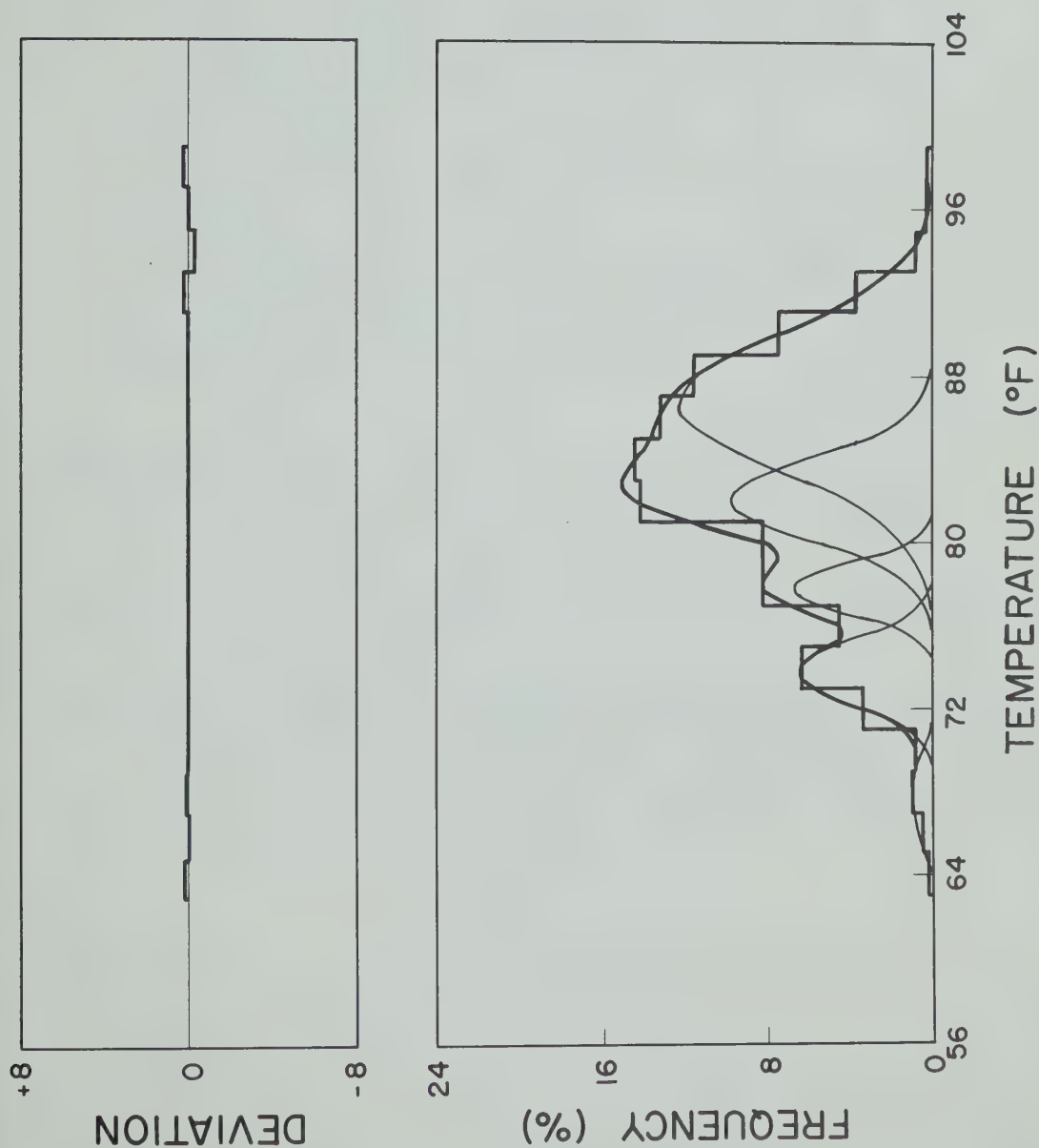


Figure 2. Least squares estimates of the partial collective parameters for Pittsburgh, Pa.

from the least squares estimates of the partial collective parameters. The vector of residuals clearly portrays the nearly perfect fit of the model estimates to the observed histogram. Table I also presents the optimum parameter estimates. One notes that the mean temperature of the warmest air mass has shifted from 88.0 to 86.8 while the remaining mean temperatures estimates were hardly modified. Larger changes occurred in the variance estimates while only minor changes for the air mass frequency estimates are noted. The results clearly show that least squares estimation can provide optimum parameter estimates and that the initial parameter estimates from Bryson's analysis are valid.

Conclusions

The ability of the partial collective model to estimate the observed probability density histogram shows one, that the mathematical model is a valid model and, two, that excellent estimates of the air mass parameters are provided by the technique of non-linear least squares estimation. The technique is presently being used in an extension of air mass analysis to additional stations and a study of the reliability of the partial collective parameter estimates has been initiated.

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| | | 2b. GROUP | |
| 3. REPORT TITLE AIRMASSES, STREAMLINES, AND THE BOREAL FOREST (APPENDIX: NON-LINEAR ESTIMATION FOR THE PARTIAL COLLECTIVE MODEL OF AIRMASS ANALYSIS). | | | |
| 4. DESCRIPTIVE NOTES (Type of report and inclusive dates) | | | |
| 5. AUTHOR(S) (Last name, first name, initial) Bryson, Reid A. Appendix: Johnson, Donald R. | | | |
| 6. REPORT DATE February 1966 | | 7a. TOTAL NO. OF PAGES 70 | 7b. NO. OF REFS 21 |
| 8a. CONTRACT OR GRANT NO. Nonr 1202(07) & NSF GP-444 | | 9a. ORIGINATOR'S REPORT NUMBER(S) Technical Report No. 24 | |
| b. PROJECT NO. NR 387-022 | | | |
| c. | | 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) | |
| d. | | | |
| 10. AVAILABILITY/LIMITATION NOTICES Distribution Unlimited | | | |
| 11. SUPPLEMENTARY NOTES | | 12. SPONSORING MILITARY ACTIVITY Geography Branch Office of Naval Research Washington, D. C. | |
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